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(54) **AIRFOILS FOR GAS TURBINE ENGINES**

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F01D 5/18 (2006.01)
F01D 25/12 (2006.01)

(52) **U.S. Cl.**
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(2013.01); **F01D 25/12** (2013.01); **F05D**
2220/32 (2013.01); **F05D 2240/30** (2013.01);
F05D 2240/306 (2013.01); **F05D 2240/307**
(2013.01); **F05D 2260/202** (2013.01)

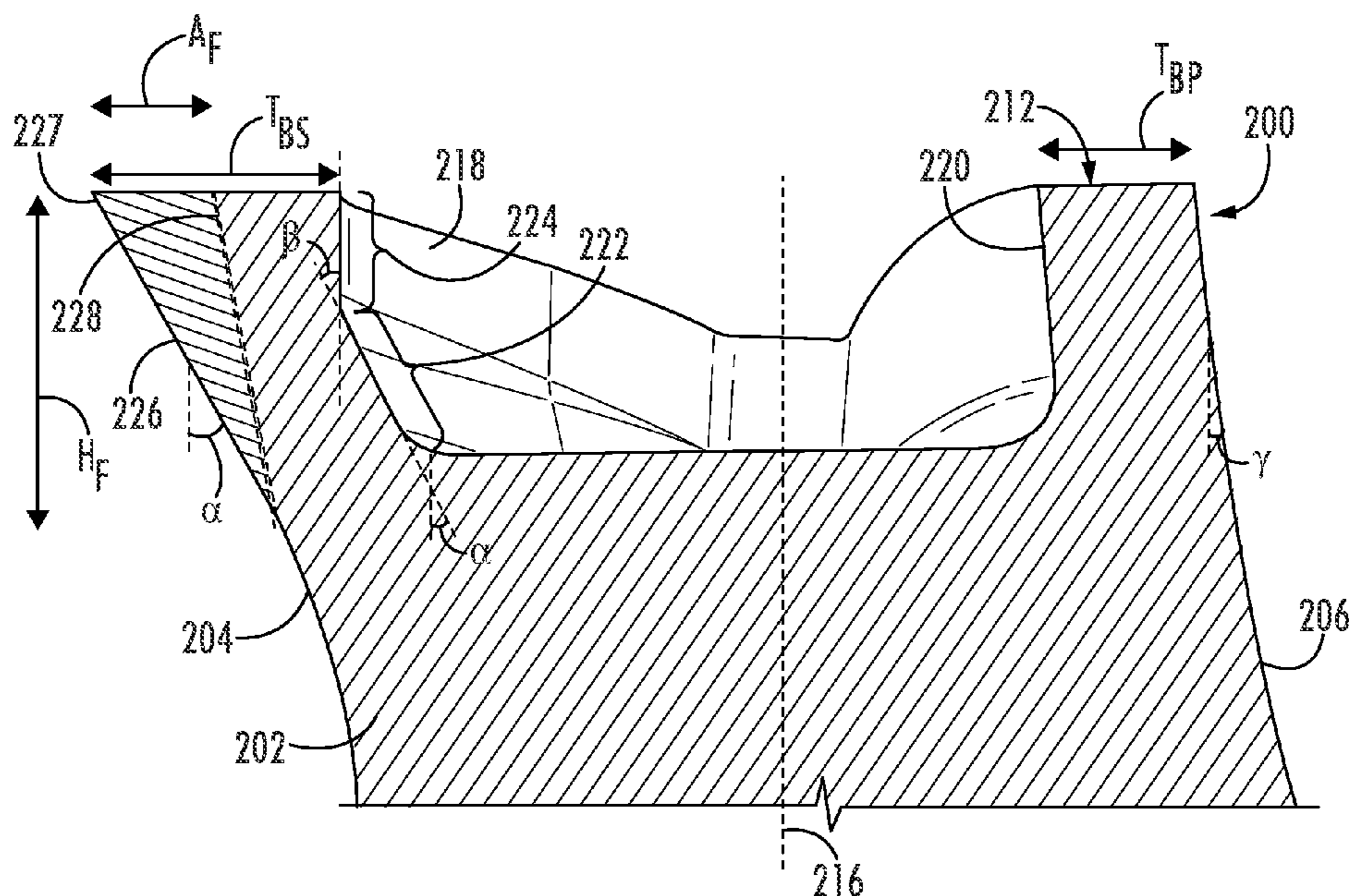
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CPC . F01D 5/186; F01D 5/187; F01D 5/20; F05D
2240/306; F05D 2240/307
See application file for complete search history.

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(57) **ABSTRACT**

An airfoil for a gas turbine engine defining a radial direction and an axial direction, the airfoil including: a flared portion extending from a suction surface of the airfoil at an outer edge of the airfoil along the radial direction; and a plenum disposed at the outer edge of the airfoil, the plenum having a suction-side sidewall and a pressure-side sidewall, wherein the suction-side sidewall has a first sidewall portion adjacent to a second sidewall portion disposed outside of the first sidewall portion along the radial direction, wherein the first sidewall portion defines a first angle, wherein the second sidewall portion defines a second angle, and wherein the first angle is greater than the second angle.

17 Claims, 6 Drawing Sheets



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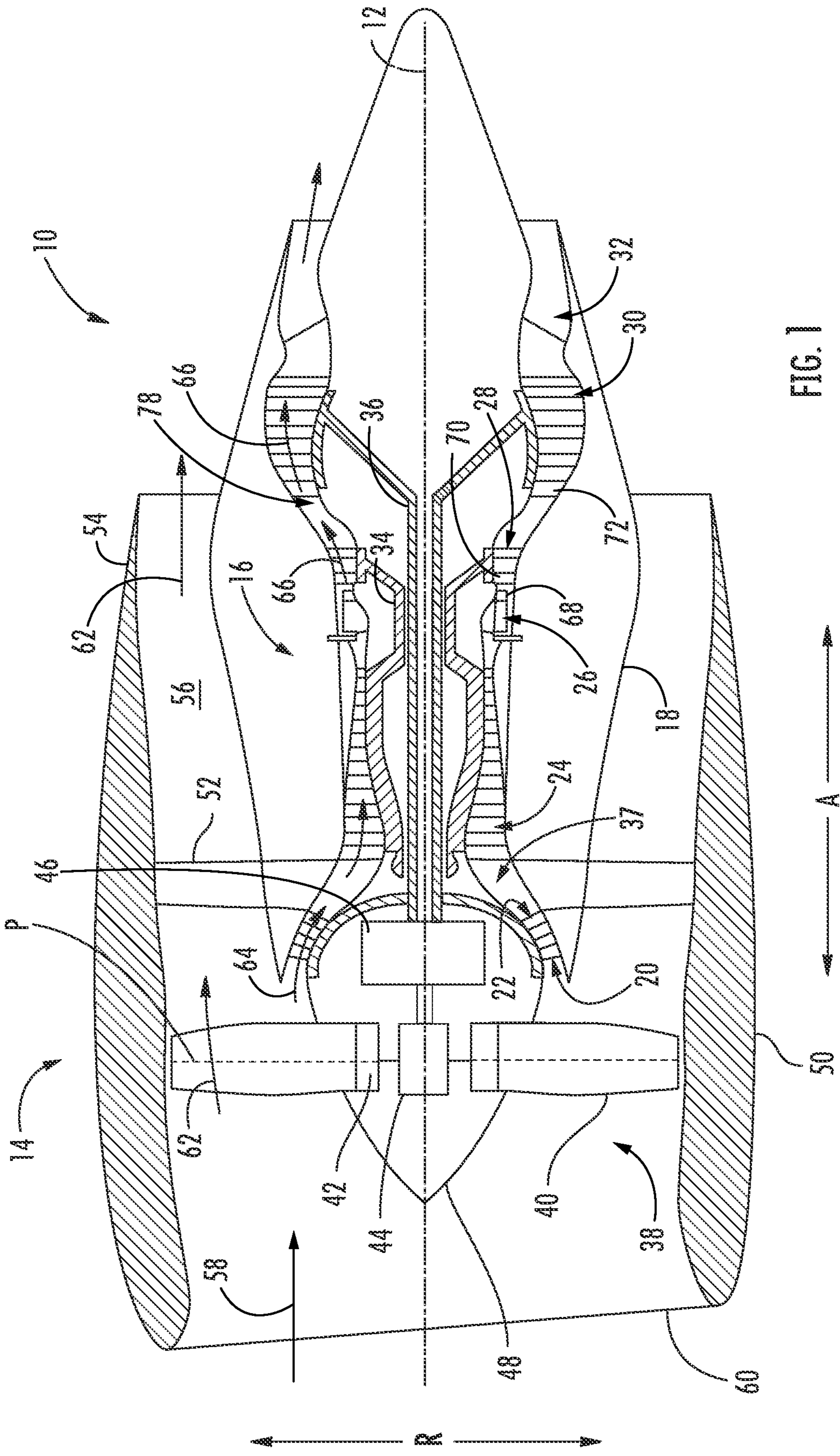


FIG. 1

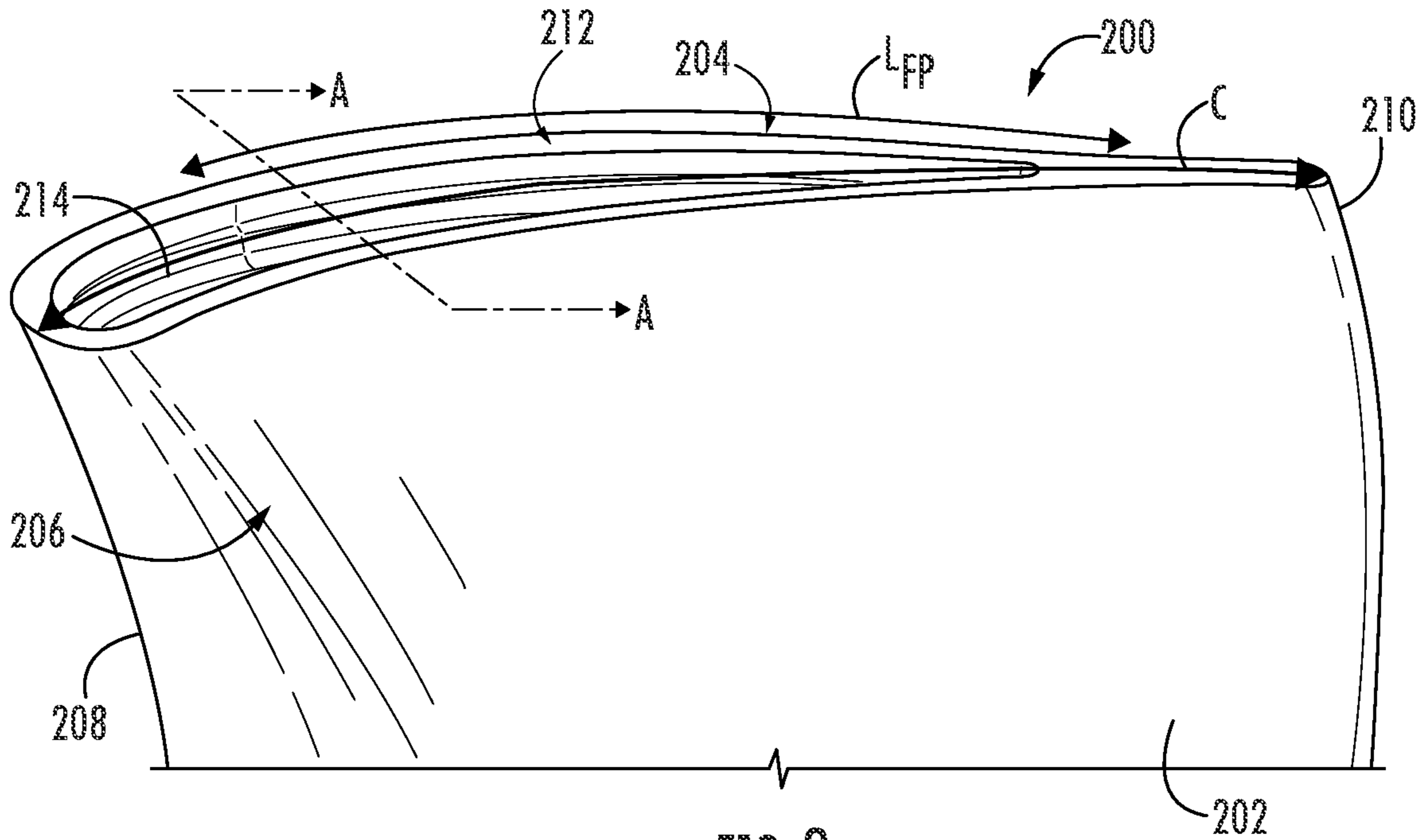


FIG. 2

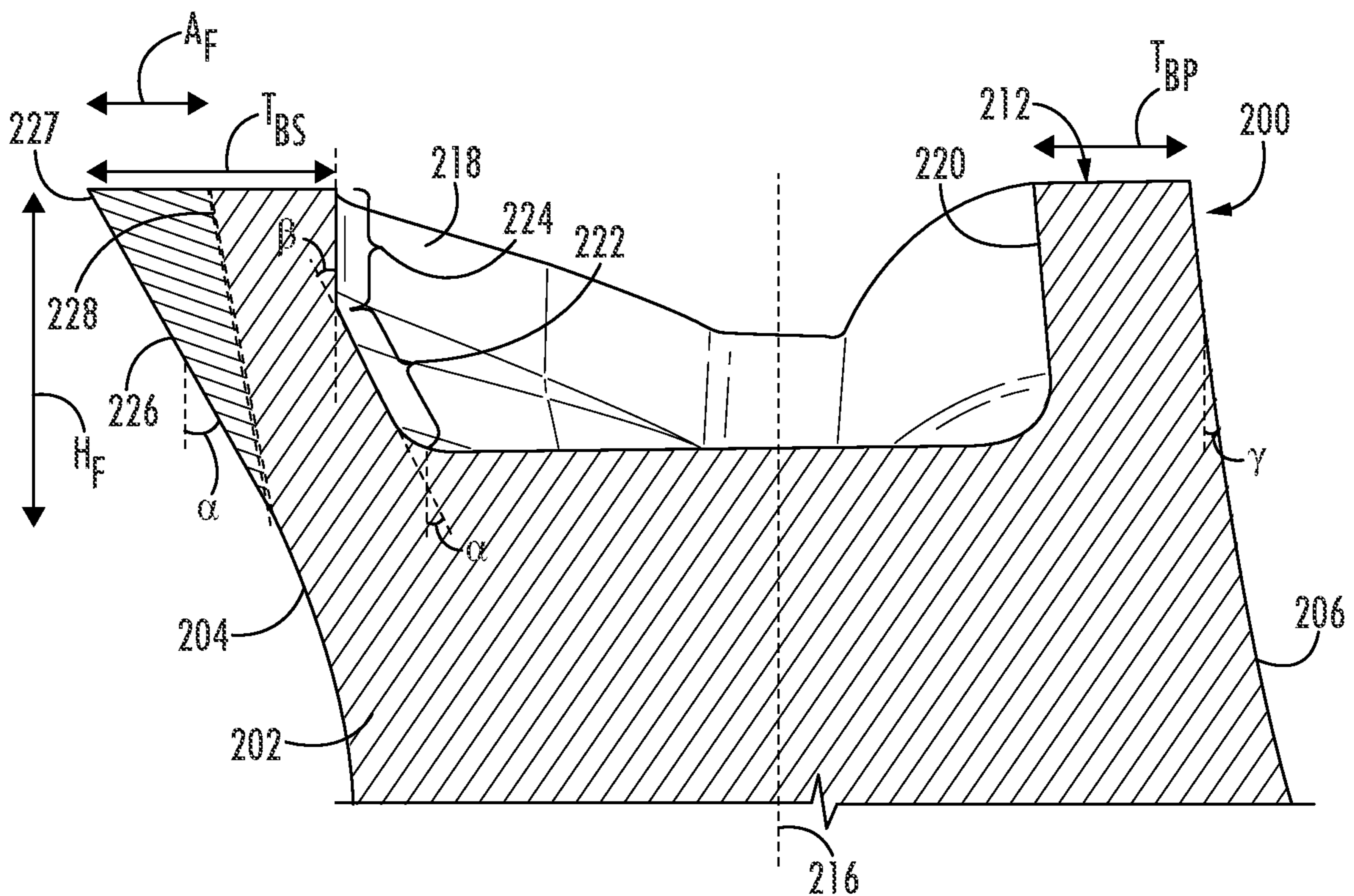


FIG. 3

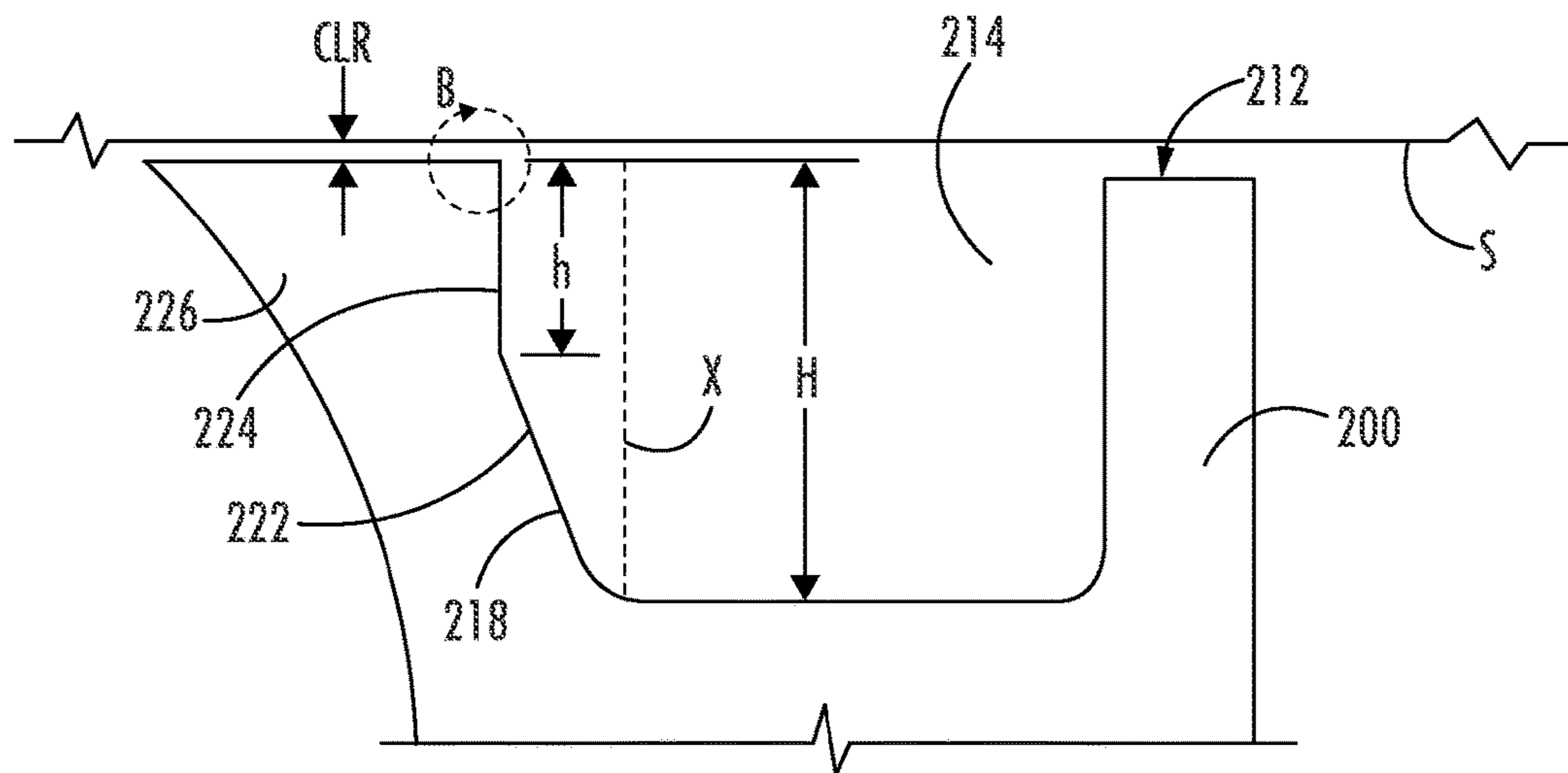


FIG. 4

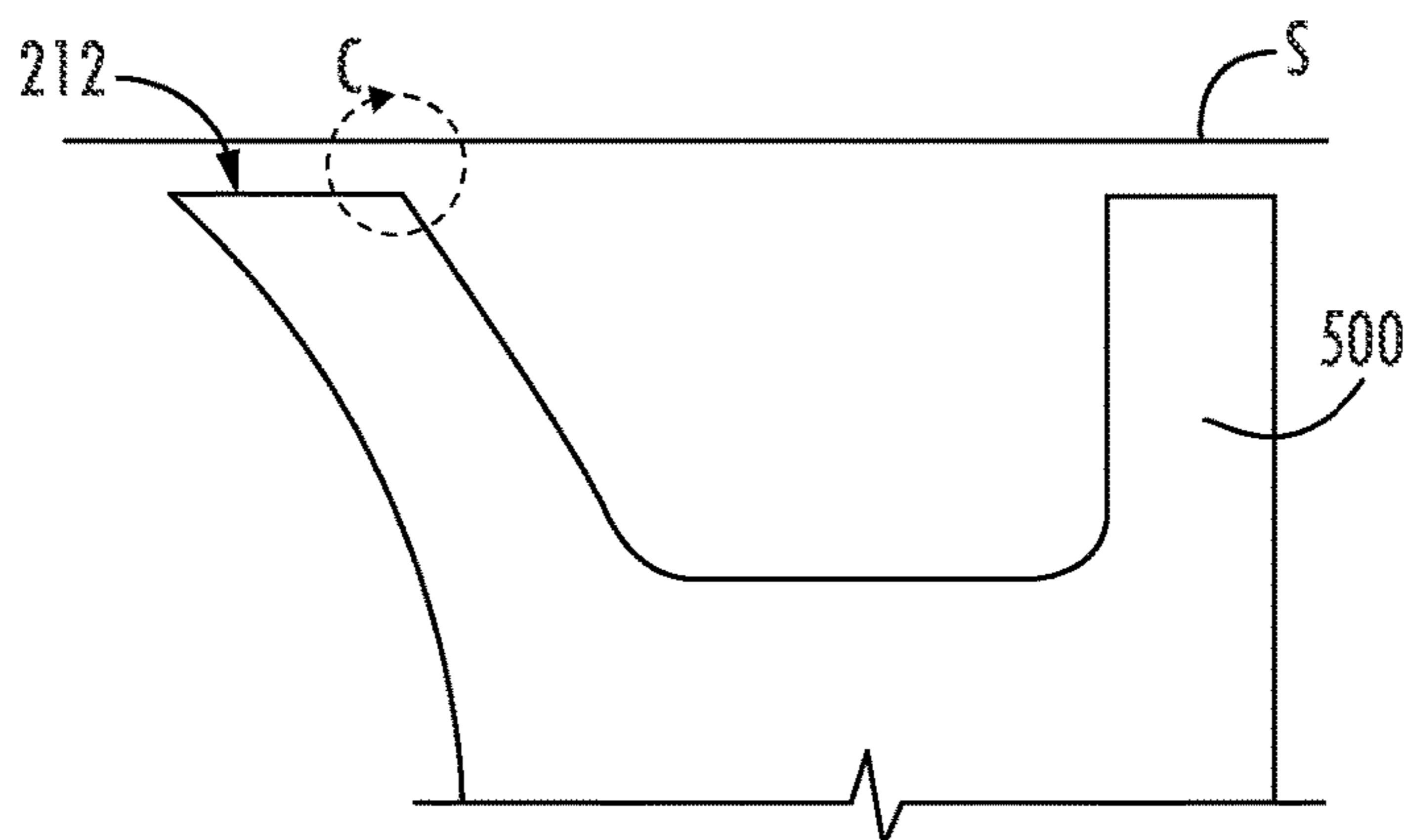


FIG. 5

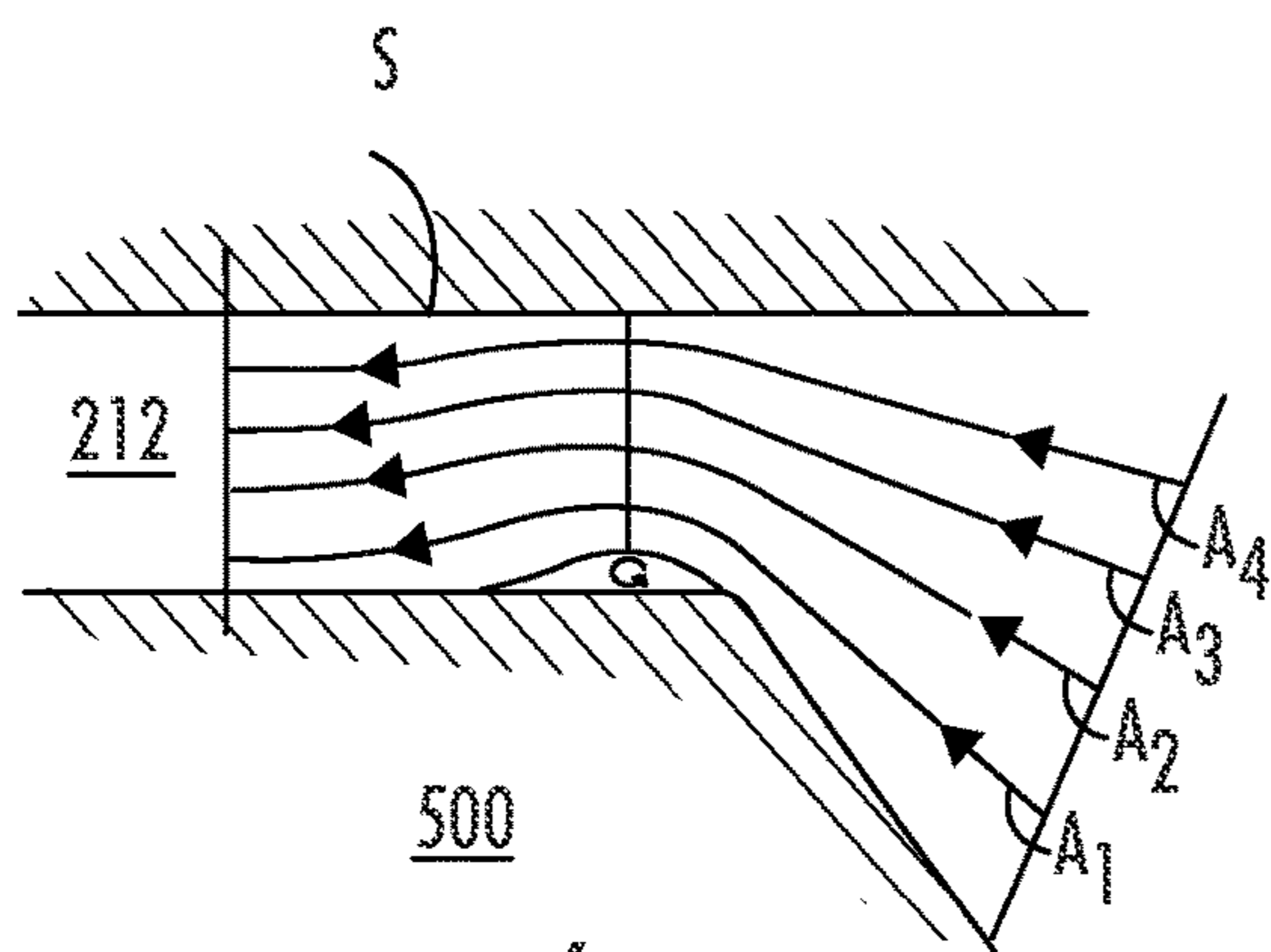


FIG. 6

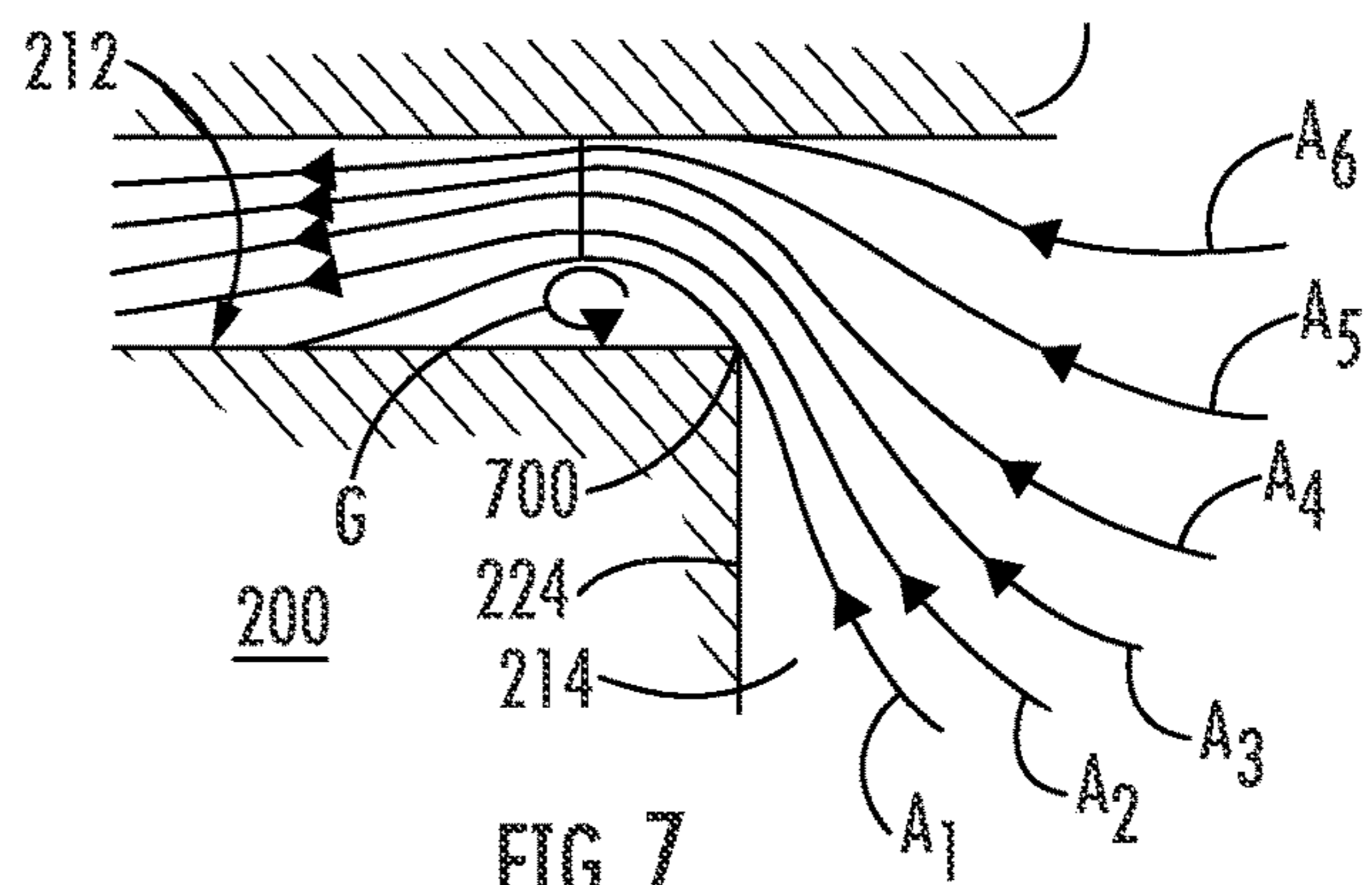
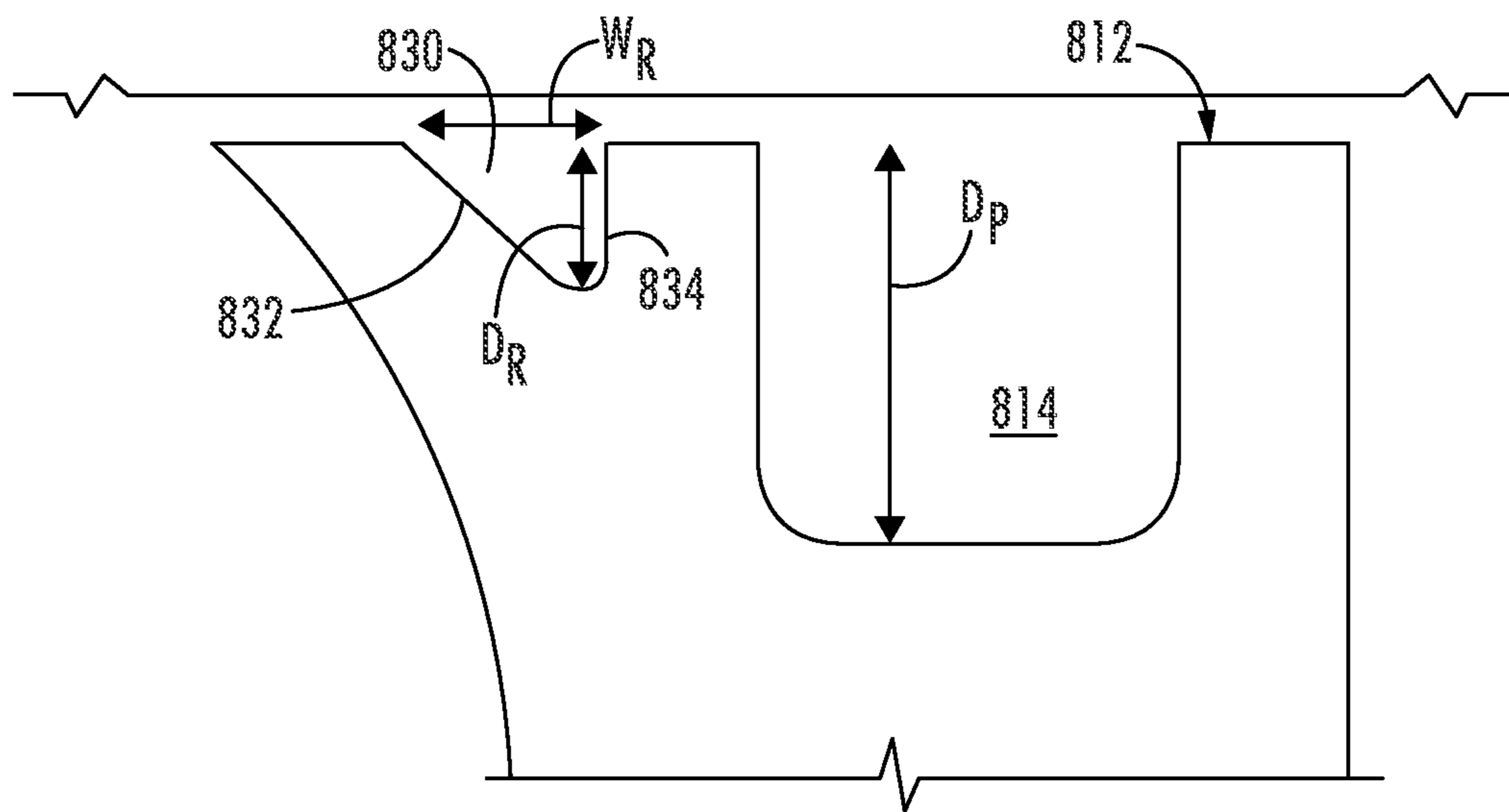
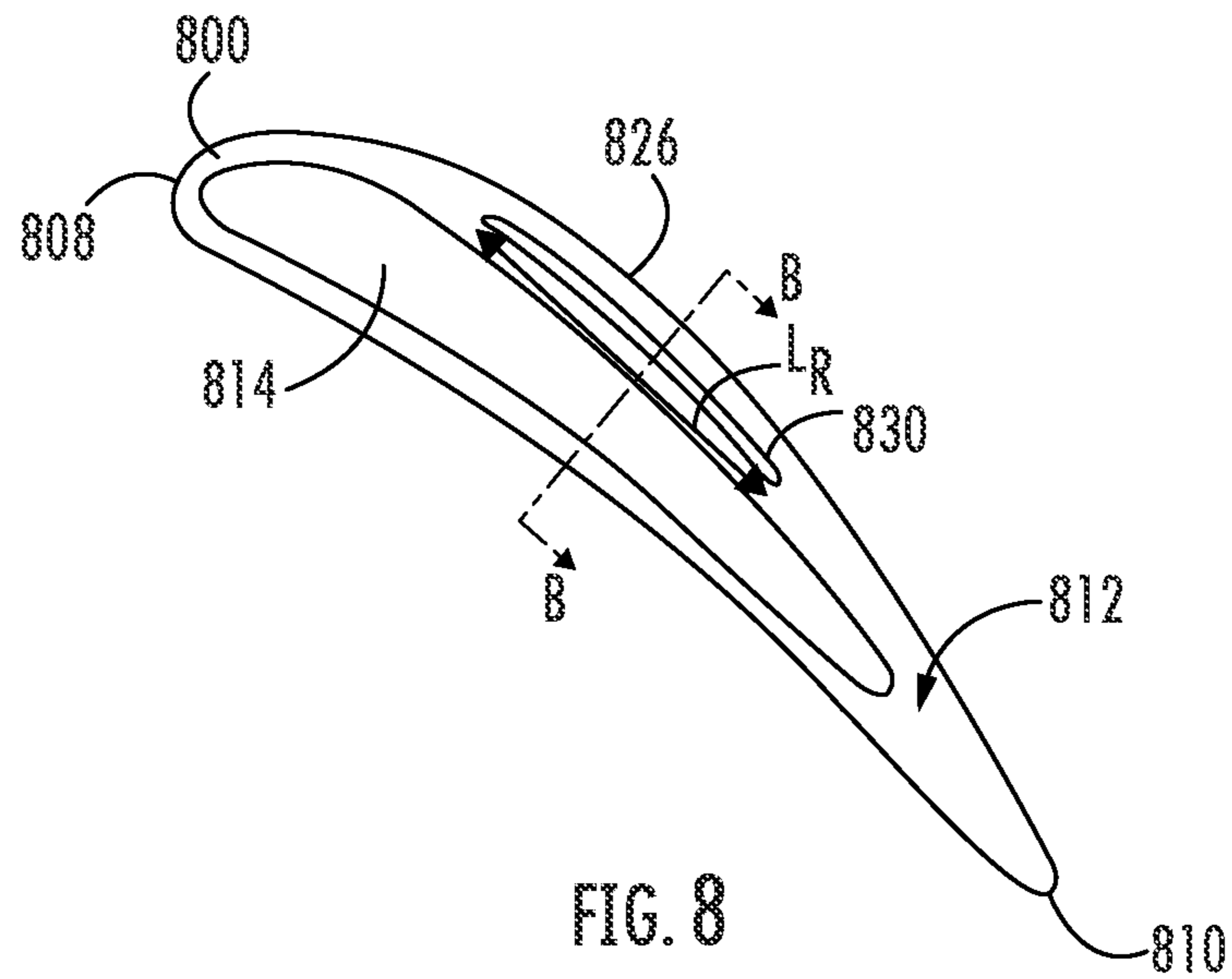


FIG. 7



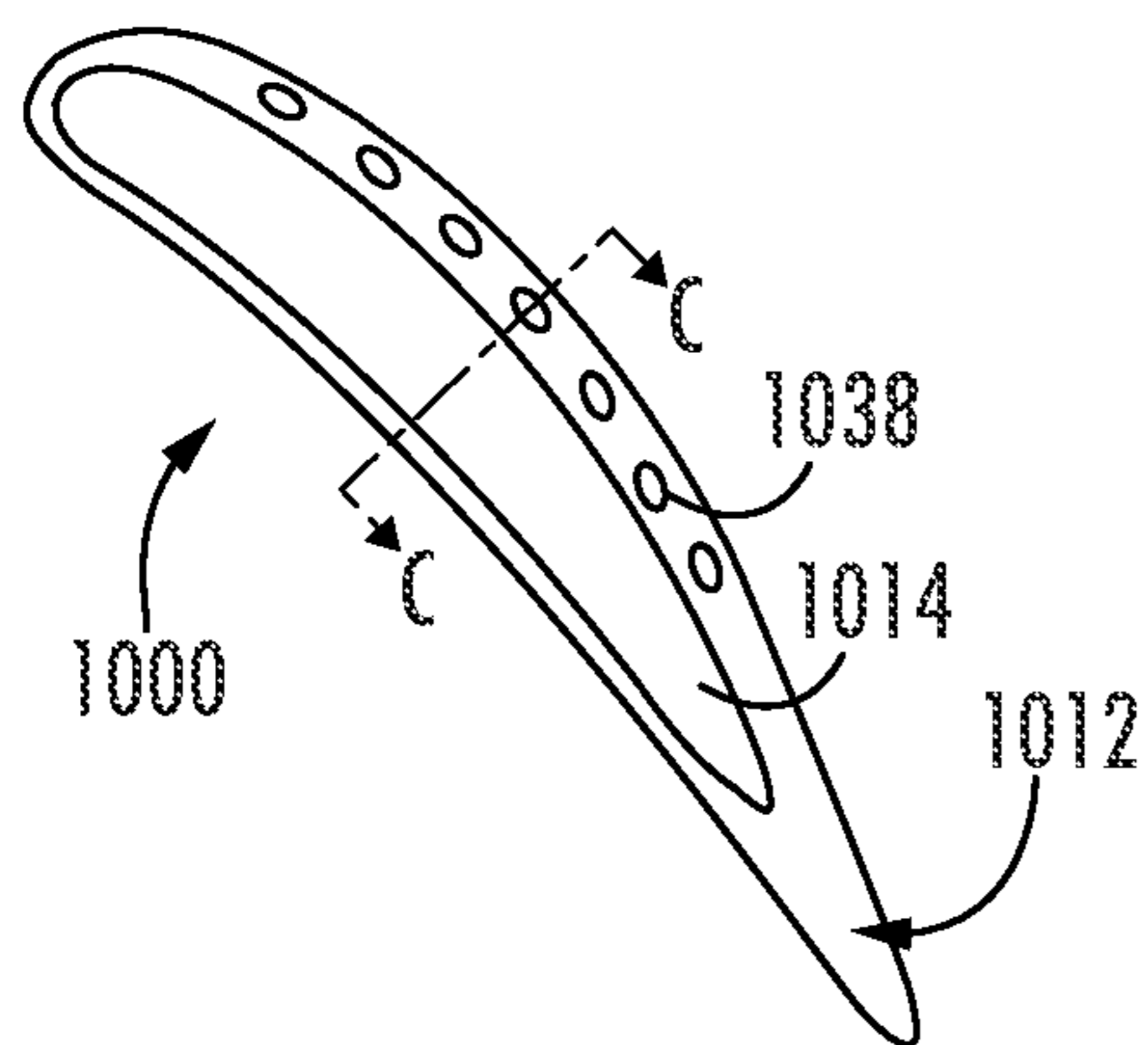


FIG. 10

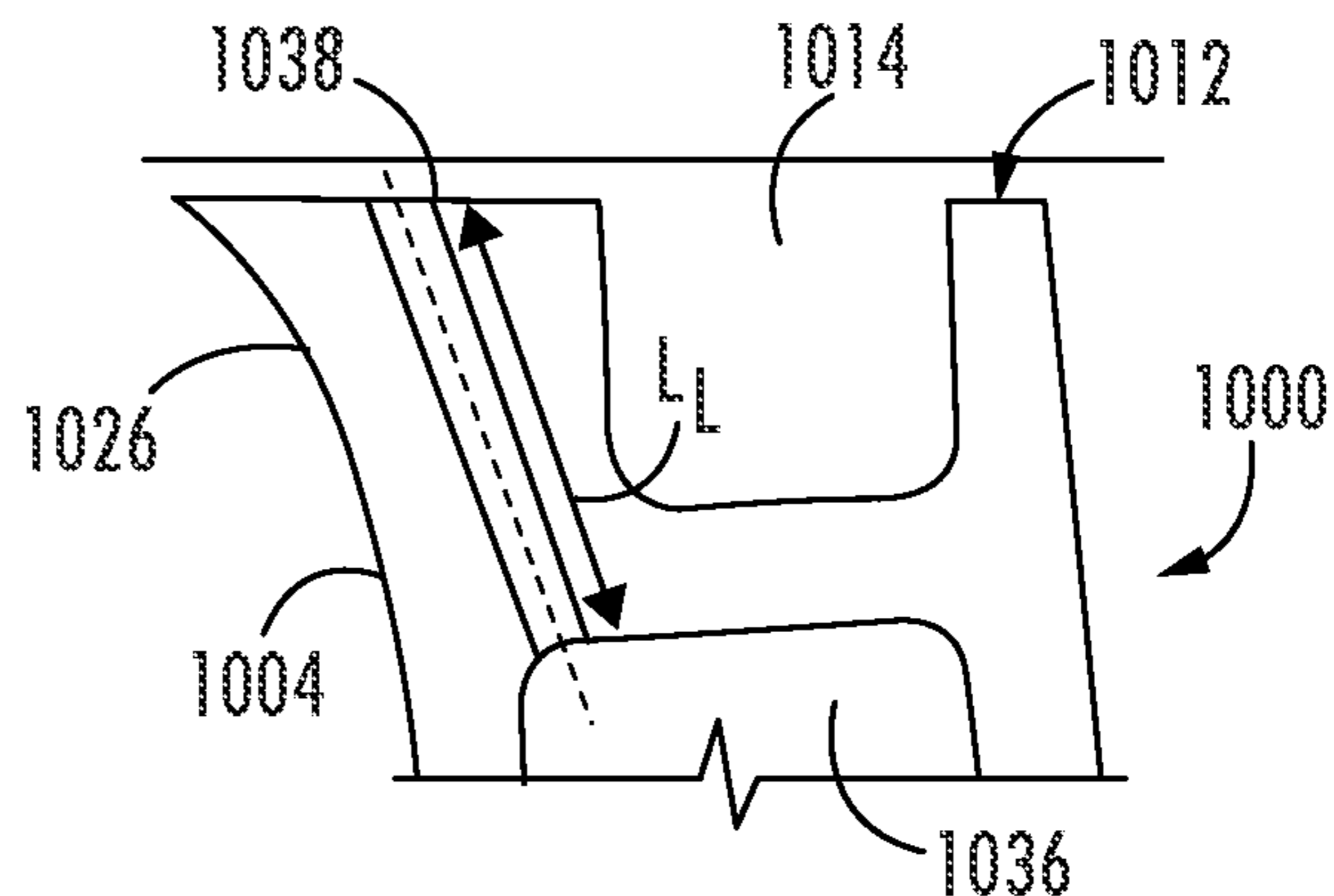


FIG. 11

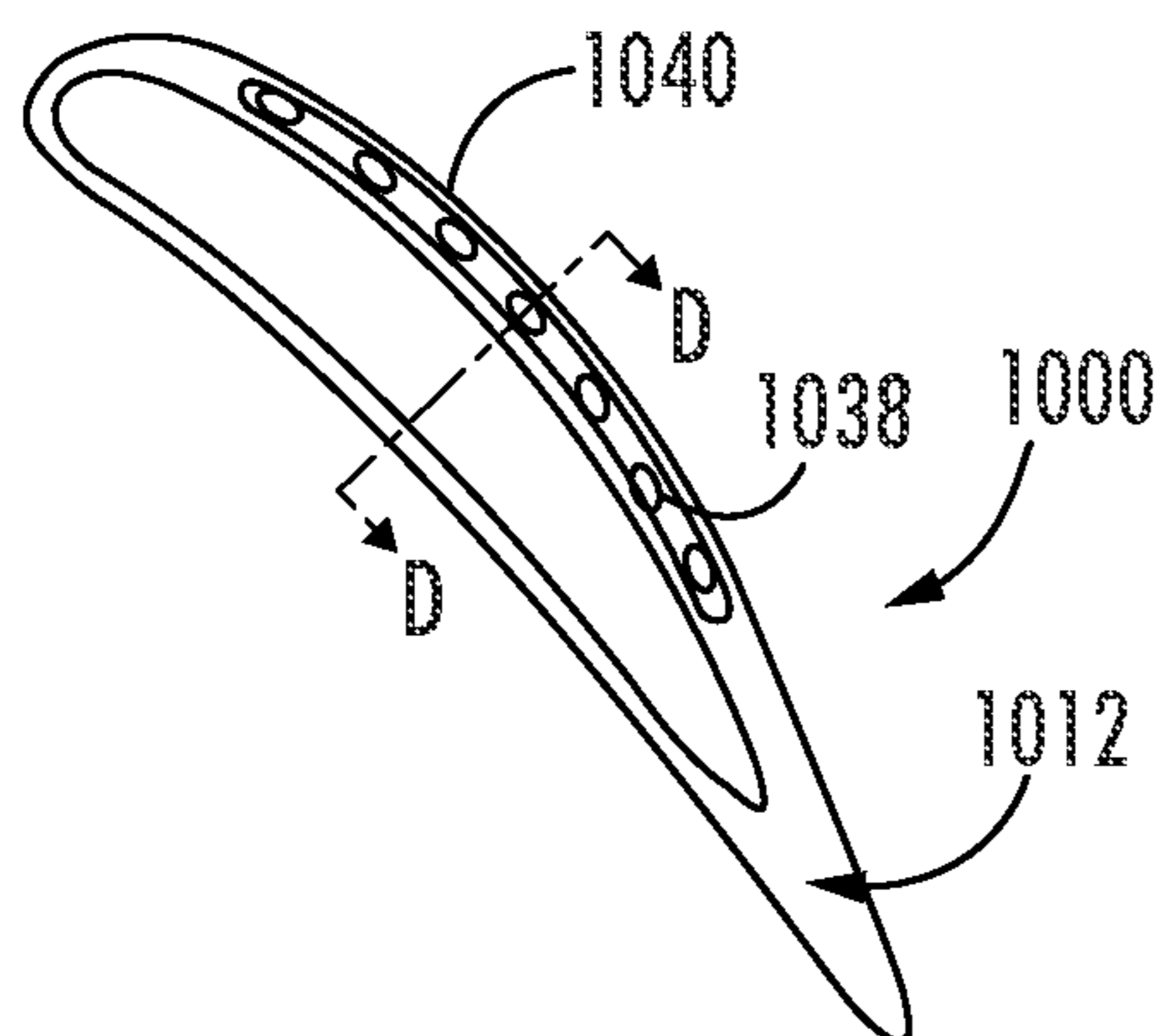


FIG. 12

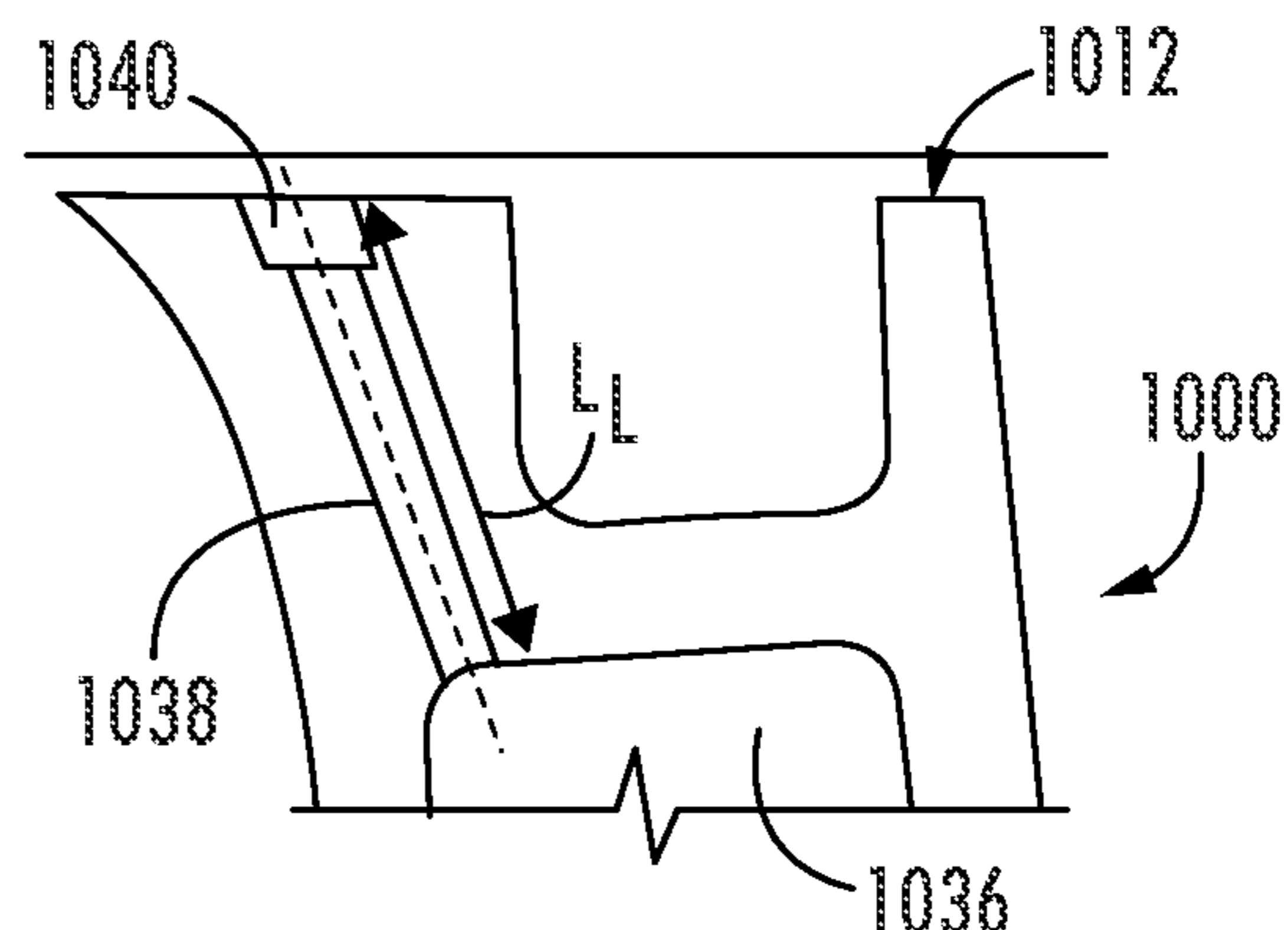


FIG. 13

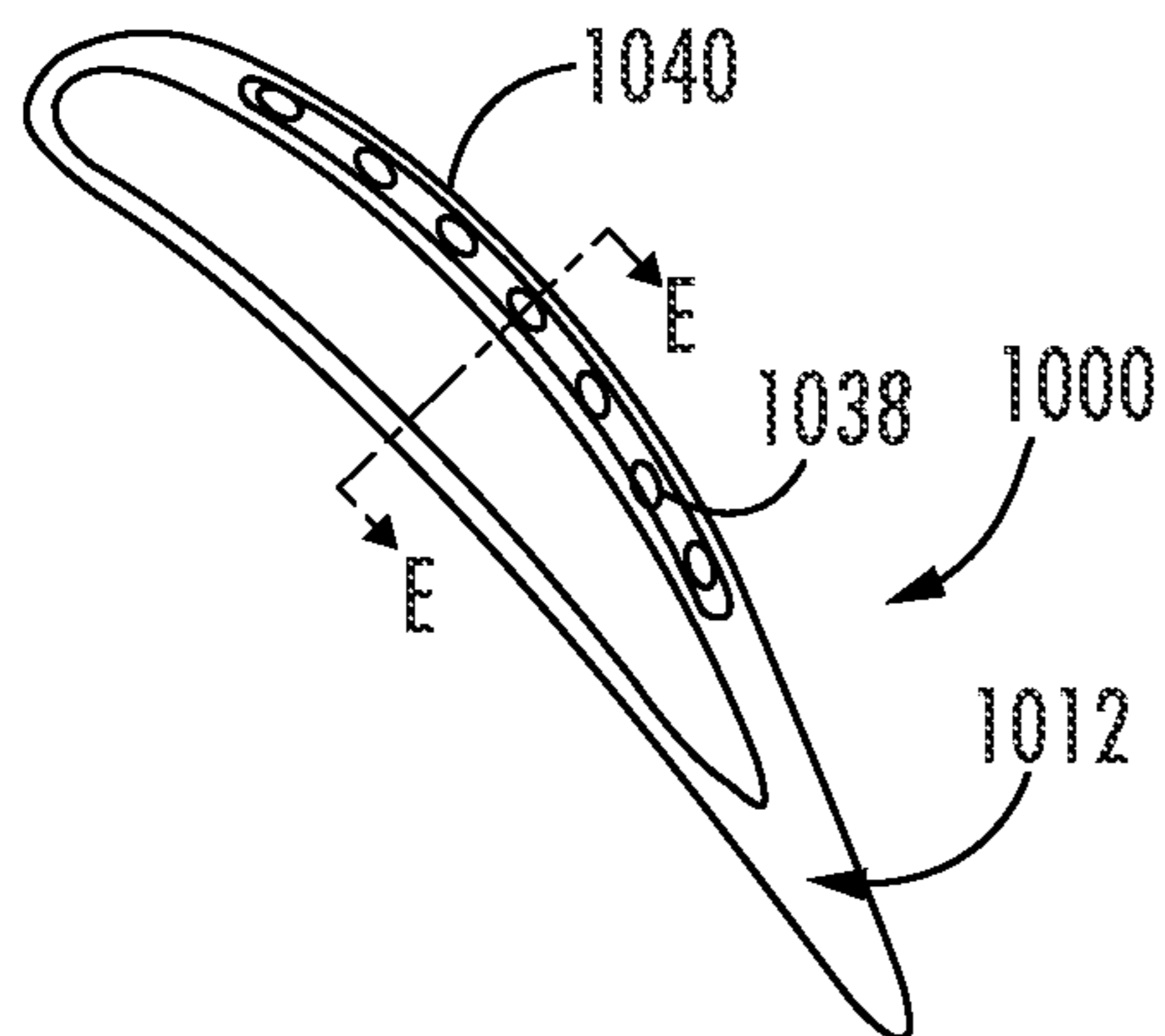


FIG. 14

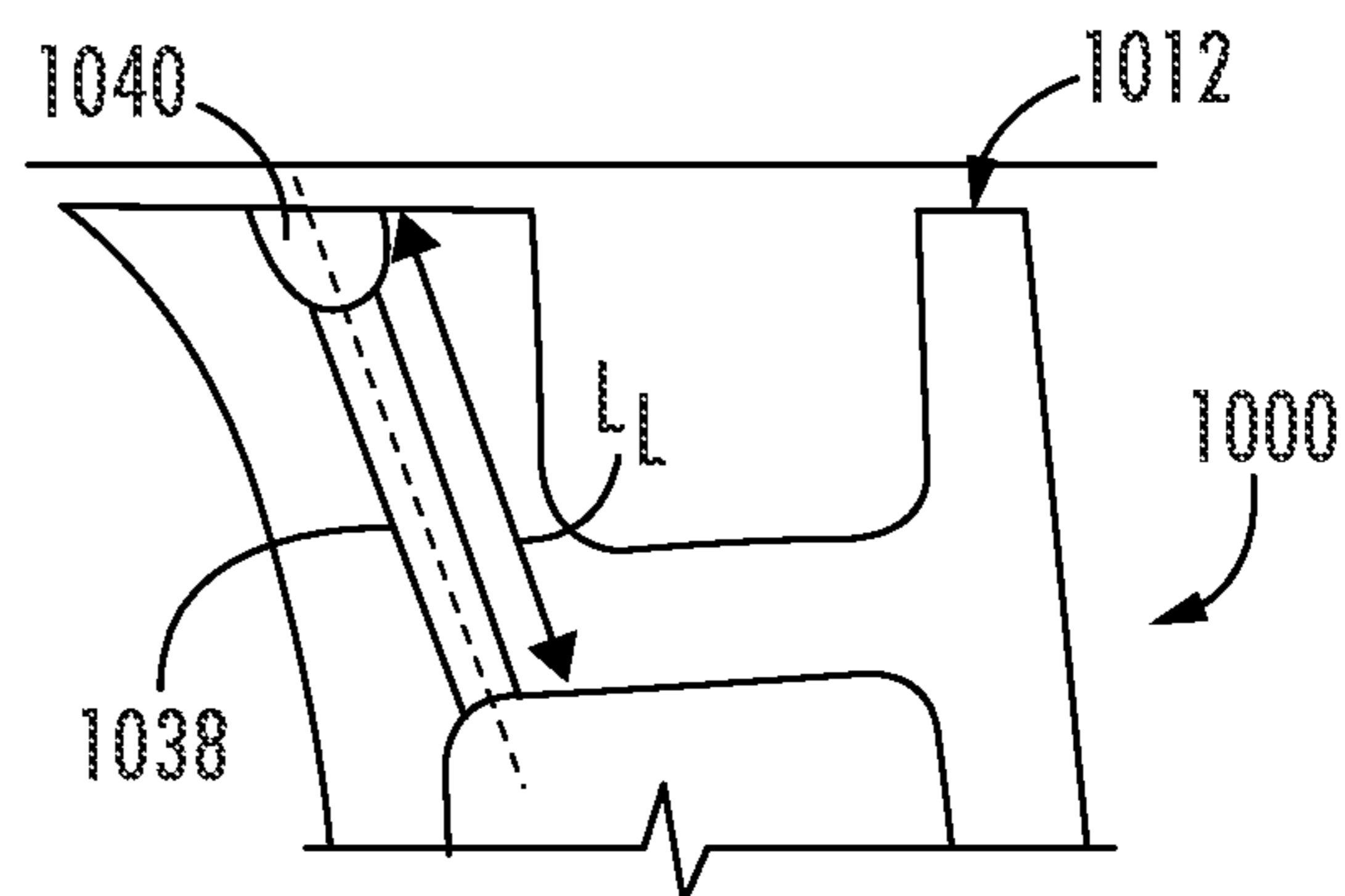


FIG. 15

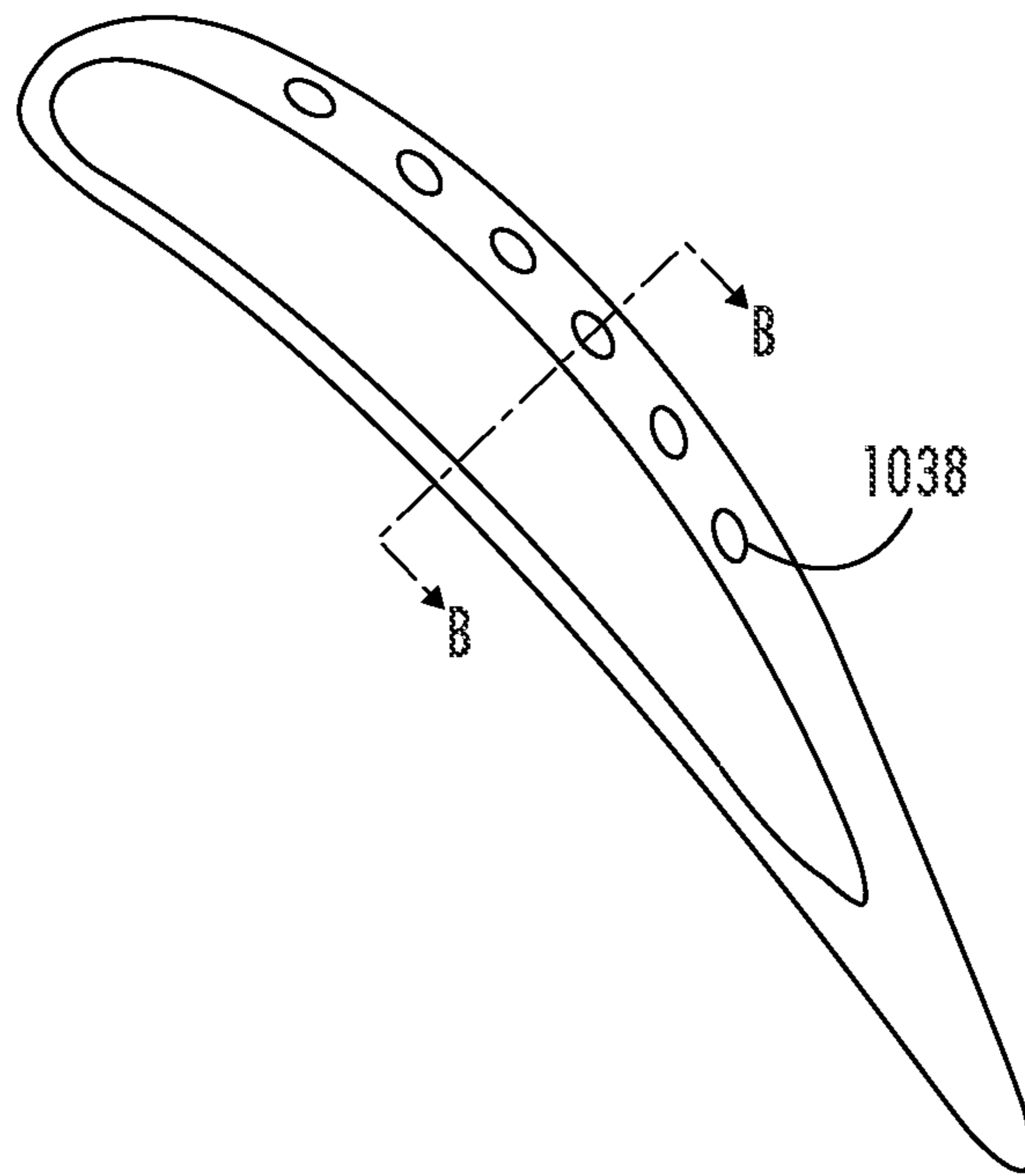


FIG. 16

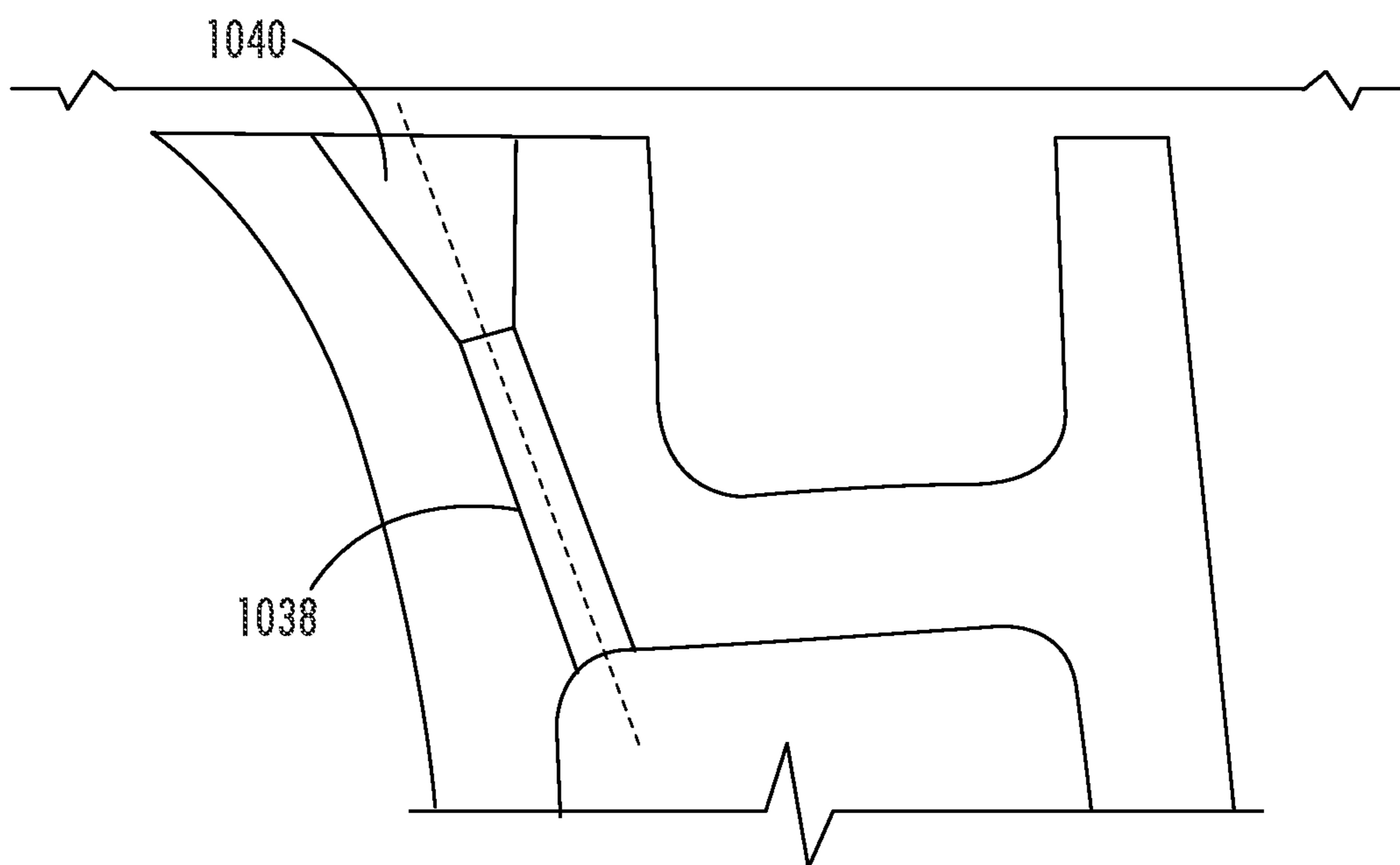


FIG. 17

AIRFOILS FOR GAS TURBINE ENGINES

FEDERALLY SPONSORED RESEARCH

This invention was made with Government support under W58RGZ-16-C-0047 awarded by the U.S. Army. The Government has certain rights in this invention.

FIELD

The present subject matter relates generally to airfoils for gas turbine engines.

BACKGROUND

Gas turbine engines include a compressor that provides pressurized air to a combustor wherein the air is mixed with fuel and ignited for generating hot combustion gases. These gases flow downstream to one or more turbines that extract energy therefrom to power the compressor and provide useful work such as powering an aircraft in flight. In a turbofan engine, which typically includes a fan placed at the front of the core engine, a high pressure turbine powers the compressor of the core engine. A low pressure turbine is disposed downstream from the high pressure turbine for powering the fan. Each turbine stage commonly includes a stationary turbine nozzle followed by a turbine rotor.

Each turbine rotor carries a circumferential array of airfoil-shaped turbine blades adapted to extract energy from the combustion gases exiting the core. These blades are typically constructed by casting from high-temperature resistant alloys (e.g. "superalloys"). The first rotor stage, immediately downstream of the combustor, is usually internally cooled and has a hollow interior with one or more serpentine passages, film cooling holes, trailing edge slots or holes, and the like. The subsequent rotor stages are not subject to the extreme high temperature of the first stage and thus may not require cooling or the same degree of cooling. To reduce the weight of the later-stage airfoils, they often include a hollowed-out portion referred to as a plenum.

The interface between the blade and shroud of the gas turbine engine affects the performance of the gas turbine engine. Accordingly, there is a need for a blade having low weight while maintaining high strength and having improved aerodynamic performance.

BRIEF DESCRIPTION

Aspects and advantages of the invention will be set forth in part in the following description, or may be obvious from the description, or may be learned through practice of the invention.

In one exemplary aspect of the present disclosure, an airfoil for a gas turbine engine defining a radial direction and an axial direction comprises a flared portion extending from a suction surface of the airfoil at an outer edge of the airfoil along the radial direction; and a plenum disposed at the outer edge of the airfoil, the plenum having a suction-side sidewall and a pressure-side sidewall, wherein the suction-side sidewall has a first sidewall portion adjacent to a second sidewall portion disposed outside of the first sidewall portion along the radial direction, wherein the first sidewall portion defines a first angle with a radial direction of the airfoil as measured by an average angular offset between the radial direction and the first sidewall portion, wherein the second sidewall portion defines a second angle with the radial direction of the airfoil as measured by an average angular offset between the

radial direction and the second sidewall portion, and wherein the first angle is greater than the second angle.

In another exemplary aspect of the present disclosure, a gas turbine engine defining a radial direction comprises a shroud; and a turbine positioned at least partially inward of the shroud along the radial direction, the turbine having a plurality of turbine rotor blades, wherein at least one of the plurality of turbine rotor blades comprises a flared portion extending from a suction surface of the airfoil at an outer edge of the airfoil; and a plenum disposed at the outer edge of the airfoil, the plenum having a suction-side sidewall and a pressure-side sidewall, wherein the suction-side sidewall has a first sidewall portion adjacent to a second sidewall portion disposed radially outside of the first sidewall portion, wherein the second sidewall portion is approximately normal relative to an inner surface of the shroud, and wherein the first sidewall portion is angularly offset from the second sidewall portion.

In another exemplary aspect of the present disclosure, an airfoil for a gas turbine engine defining a radial direction and an axial direction comprising a flared portion extending from a suction surface of the airfoil along less than 20% of a radial length of the airfoil, as measured from an outer edge of the airfoil along the radial direction, wherein the flared portion extends less than 80% of a chord length, c , of the airfoil, as measured at the outer edge of the airfoil.

These and other features, aspects and advantages of the present invention will become better understood with reference to the following description and appended claims. The accompanying drawings, which are incorporated in and constitute part of this specification, illustrate embodiments of the invention and, together with the description, serve to explain the principles of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

A full and enabling disclosure of the present invention, including the best mode thereof, directed to one of ordinary skill in the art, is set forth in the specification, which makes reference to the appended FIGS., in which:

FIG. 1 is a schematic cross-sectional view of an exemplary gas turbine engine incorporating an exemplary embodiment of a turbine section according to an exemplary embodiment of the present disclosure.

FIG. 2 is perspective view of a portion of an airfoil for a gas turbine engine according to an exemplary embodiment of the present disclosure.

FIG. 3 is a cross-sectional view of the airfoil as seen along Line A-A in FIG. 2 in accordance with an exemplary embodiment of the present disclosure.

FIG. 4 is a cross-sectional view of a portion of an airfoil disposed within a gas turbine engine according to an exemplary embodiment of the present disclosure.

FIG. 5 is a cross-sectional view of a portion of an airfoil disposed within a gas turbine engine according to an exemplary embodiment of the present disclosure.

FIG. 6 is an enlarged view of a portion of the airfoil and gas turbine engine as seen in Circle C in FIG. 5 in accordance with an exemplary embodiment of the present disclosure.

FIG. 7 is an enlarged view of a portion of the airfoil and gas turbine engine as seen in Circle B in FIG. 4 in accordance with an exemplary embodiment of the present disclosure.

FIG. 8 is a top view of an airfoil as seen from an outer edge according to an exemplary embodiment of the present disclosure.

FIG. 9 is a cross-sectional view of the airfoil of FIG. 8 as seen along Line B-B according to an exemplary embodiment of the present disclosure.

FIG. 10 is a top view of an airfoil as seen from an outer edge according to an exemplary embodiment of the present disclosure.

FIG. 11 is a cross-sectional view of the airfoil of FIG. 10 as seen along Line C-C according to an exemplary embodiment of the present disclosure.

FIG. 12 is a top view of an airfoil as seen from an outer edge according to an exemplary embodiment of the present disclosure.

FIG. 13 is a cross-sectional view of the airfoil of FIG. 12 as seen along Line D-D according to an exemplary embodiment of the present disclosure.

FIG. 14 is a top view of an airfoil as seen from an outer edge according to an exemplary embodiment of the present disclosure.

FIG. 15 is a cross-sectional view of the airfoil of FIG. 14 as seen along Line E-E according to an exemplary embodiment of the present disclosure.

FIG. 16 is a top view of an airfoil as seen from an outer edge according to an exemplary embodiment of the present disclosure.

FIG. 17 is a cross-sectional view of the airfoil of FIG. 16 as seen along Line F-F according to an exemplary embodiment of the present disclosure.

DETAILED DESCRIPTION

Reference will now be made in detail to present embodiments of the invention, one or more examples of which are illustrated in the accompanying drawings. The detailed description uses numerical and letter designations to refer to features in the drawings. Like or similar designations in the drawings and description have been used to refer to like or similar parts of the invention.

As used herein, the terms “first”, “second”, and “third” may be used interchangeably to distinguish one component from another and are not intended to signify location or importance of the individual components.

The terms “forward” and “aft” refer to relative positions within a gas turbine engine or vehicle, and refer to the normal operational attitude of the gas turbine engine or vehicle. For example, with regard to a gas turbine engine, forward refers to a position closer to an engine inlet and aft refers to a position closer to an engine nozzle or exhaust.

The terms “upstream” and “downstream” refer to the relative direction with respect to fluid flow in a fluid pathway. For example, “upstream” refers to the direction from which the fluid flows, and “downstream” refers to the direction to which the fluid flows.

The terms “coupled,” “fixed,” “attached to,” and the like refer to both direct coupling, affixing, or attaching, as well as indirect coupling, affixing, or attaching through one or more intermediate components or features, unless otherwise specified herein.

The singular forms “a”, “an”, and “the” include plural references unless the context clearly dictates otherwise.

Approximating language, as used herein throughout the specification and claims, is applied to modify any quantitative representation that could permissibly vary without resulting in a change in the basic function to which it is related. Accordingly, a value modified by a term or terms, such as “about”, “approximately”, and “substantially”, are not to be limited to the precise value specified. In at least some instances, the approximating language may corre-

spond to the precision of an instrument for measuring the value, or the precision of the methods or machines for constructing or manufacturing the components and/or systems. For example, the approximating language may refer to being within a 10 percent margin.

Here and throughout the specification and claims, range limitations are combined and interchanged, such ranges are identified and include all the sub-ranges contained therein unless context or language indicates otherwise. For example, all ranges disclosed herein are inclusive of the endpoints, and the endpoints are independently combinable with each other.

In general, rotor blades (referred to herein as airfoils) are used in gas turbine engines to convert between axial and rotational forces. Aerodynamic characteristics of airfoils can affect engine performance and efficiency. Airfoils described in accordance with embodiments herein can generally include flared portions along the suction surface sidewall. The flared portion can extend from the outer edge of the airfoil in an axial direction of the gas turbine engine, creating a desirable aerodynamic effect which increases engine performance and efficiency. In some embodiments, a plenum disposed at the outer edge of the airfoil can have a multi-segmented sidewall to further increase desirable aerodynamic characteristics while reducing unnecessary weight of the airfoil. In addition, one or more cooling elements, such as recesses and/or cooling holes, can extend from the radially outer surface of the airfoil to a cooling cavity in order to further enhance aerodynamic performance of the gas turbine engine.

Inclusion of an airfoil in accordance with such configuration including, e.g., a flared portion along the suction surface sidewall may result in a more aerodynamically capable airfoil, permitting increased engine performance and efficiency. Further, inclusion of an airfoil in accordance with other aspects of such a configuration may result in an airfoil having a reduced weight and increased cooling characteristics.

Referring now to the drawings, wherein identical numerals indicate the same elements throughout the figures, FIG. 1 is a schematic cross-sectional view of a gas turbine engine in accordance with an exemplary embodiment of the present disclosure. More particularly, for the embodiment of FIG. 1, the gas turbine engine is a high-bypass turbofan jet engine 10, referred to herein as “turbofan engine 10.” As shown in FIG. 1, the turbofan engine 10 defines an axial direction A (extending parallel to a longitudinal centerline 12 provided for reference), a radial direction R, and a circumferential direction (i.e., a direction extending about the axial direction A; not depicted). In general, the turbofan 10 includes a fan section 14 and a core turbine engine 16 disposed downstream from the fan section 14.

The exemplary core turbine engine 16 depicted generally includes a substantially tubular outer casing 18 that defines an annular inlet 20. The outer casing 18 encases, in serial flow relationship, a compressor section including a booster or low pressure (LP) compressor 22 and a high pressure (HP) compressor 24; a combustion section 26; a turbine section including a high pressure (HP) turbine 28 and a low pressure (LP) turbine 30; and a jet exhaust nozzle section 32. The compressor section, combustion section 26, and turbine section together define a core air flowpath 37 extending from the annular inlet 20 through the LP compressor 22, HP compressor 24, combustion section 26, HP turbine section 28, LP turbine section 30 and jet nozzle exhaust section 32. A high pressure (HP) shaft or spool 34 drivingly connects

the HP turbine **28** to the HP compressor **24**. A low pressure (LP) shaft or spool **36** drivingly connects the LP turbine **30** to the LP compressor **22**.

For the embodiment depicted, the fan section **14** includes a variable pitch fan **38** having a plurality of fan blades **40** coupled to a disk **42** in a spaced apart manner. As depicted, the fan blades **40** extend outwardly from disk **42** generally along the radial direction R. Each fan blade **40** is rotatable relative to the disk **42** about a pitch axis P by virtue of the fan blades **40** being operatively coupled to a suitable actuation member **44** configured to collectively vary the pitch of the fan blades **40**, e.g., in unison. The fan blades **40**, disk **42**, and actuation member **44** are together rotatable about the longitudinal axis **12** by LP shaft **36** across a power gear box **46**. The power gear box **46** includes a plurality of gears for stepping down the rotational speed of the LP shaft **36** to a more efficient rotational fan speed.

Referring still to the exemplary embodiment of FIG. 1, the disk **42** is covered by rotatable front spinner cone **48** aerodynamically contoured to promote an airflow through the plurality of fan blades **40**. Additionally, the exemplary fan section **14** includes an annular fan casing or outer nacelle **50** that circumferentially surrounds the fan **38** and/or at least a portion of the core turbine engine **16**. It should be appreciated that for the embodiment depicted, the nacelle **50** is supported relative to the core turbine engine **16** by a plurality of circumferentially-spaced outlet guide vanes **52**. Moreover, a downstream section **54** of the nacelle **50** extends over an outer portion of the core turbine engine **16** so as to define a bypass airflow passage **56** therebetween.

During operation of the turbofan engine **10**, a volume of air **58** enters the turbofan **10** through an associated inlet **60** of the nacelle **50** and/or fan section **14**. As the volume of air **58** passes across the fan blades **40**, a first portion of the air **58** as indicated by arrows **62** is directed or routed into the bypass airflow passage **56** and a second portion of the air **58** as indicated by arrow **64** is directed or routed into the LP compressor **22**. The ratio between the first portion of air **62** and the second portion of air **64** is commonly known as a bypass ratio. The pressure of the second portion of air **64** is then increased as it is routed through the high pressure (HP) compressor **24** and into the combustion section **26**, where it is mixed with fuel and burned to provide combustion gases **66**.

The combustion gases **66** are routed through the HP turbine **28** where a portion of thermal and/or kinetic energy from the combustion gases **66** is extracted via sequential stages of HP turbine stator vanes **68** that are coupled to an inner casing (not shown) and HP turbine rotor blades **70** that are coupled to the HP shaft or spool **34**, thus causing the HP shaft or spool **34** to rotate, thereby supporting operation of the HP compressor **24**. The combustion gases **66** are then routed through the LP turbine **30** where a second portion of thermal and kinetic energy is extracted from the combustion gases **66** via sequential stages of a plurality of LP turbine rotor blades **72**. The plurality of LP turbine rotor blades **72** drive the LP shaft or spool **36**, thus causing the LP shaft or spool **36** to rotate. Such thereby supports operation of the LP compressor **22** and/or rotation of the fan **38**.

The combustion gases **66** are subsequently routed through the jet exhaust nozzle section **32** of the core turbine engine **16** to provide propulsive thrust. Simultaneously, the pressure of the first portion of air **62** is substantially increased as the first portion of air **62** is routed through the bypass airflow passage **56** before it is exhausted from a fan nozzle exhaust section of the turbofan **10**, also providing propulsive thrust. The HP turbine **28**, the LP turbine **30**, and the jet exhaust

nozzle section **32** at least partially define a hot gas path **78** for routing the combustion gases **66** through the core turbine engine **16**.

It should be appreciated, however, that the exemplary turbofan engine **10** depicted in FIG. 1 is by way of example only, and that in other exemplary embodiments, the turbofan engine **10** may have any other suitable configuration. For example, in other exemplary embodiments, the turbine fan engine **10** may instead be configured as any other suitable turbomachine including, e.g., any other suitable number of shafts or spools, and excluding, e.g., the power gearbox **46** and/or fan **38**, etc. Accordingly, it will be appreciated that in other exemplary embodiments, the turbofan engine **10** may instead be configured as, e.g., a turbojet engine, a turboshaft engine, a turboprop engine, etc., and further may be configured as an aeroderivative gas turbine engine or industrial gas turbine engine.

FIG. 2 is a perspective view of a radially outer portion of an exemplary airfoil **200** in accordance with an exemplary embodiment described herein. Airfoils described herein can be one of a plurality of rotor blades of a turbine on a gas turbine engine, such as the turbofan jet engine **10** previously described with respect to FIG. 1. Alternatively, the airfoil can be one of a plurality of rotor blades of a compressor on a gas turbine engine. In yet other embodiments, the airfoil may be associated with another piece of equipment on an engine. In the installed state, the airfoil can extend from a central hub of the turbine or compressor radially outward toward a shroud of the gas turbine engine.

The airfoil **200** depicted in FIG. 2, generally includes a body **202** having a suction surface **204** (sometimes referred to as the upper surface) and a pressure surface **206** (sometimes referred to as the lower surface). The suction surface **204** and pressure surface **206** can generally correspond with the shape and operational movement, e.g., rotational direction, of the airfoil **200**, with the suction surface **204** being generally associated with higher velocity and lower static pressure while the pressure surface **206** is associated with comparatively higher static pressure. The suction surface **204** and pressure surface **206** can define opposite sides of the airfoil **200** and can extend between an outer edge **212** of the airfoil **200** and a central hub of the turbine or compressor.

The body **202** of the airfoil **200** can include a leading edge **208** at the front of the airfoil **200** and a trailing edge **210** at the rear of the airfoil **200**. A chord line is represented by a straight line connecting the leading edge **208** and trailing edge **210** together. The chord length, *c*, is the length of the chord line.

The body **202** of the airfoil **200** can extend between the central hub, e.g., of a turbine, and the outer edge **212** of the airfoil **200**. When disposed within the previously described turbofan jet engine **10**, the outer edge **212** of the airfoil **200** can be spaced apart from a shroud of the turbofan jet engine **10** by a small clearance, as described hereinafter. A plenum **214** can extend from the outer edge **212** of the airfoil **200** into the body **202** to create a void at the outer edge **212** of the airfoil **200**. The void can define a volume, bounded by a plane defined by the outer edge **212**. In the illustrated embodiment, the plenum **214** is surrounded on all lateral sides by a sidewall defined by the body **202**.

The airfoil **200** is typically formed as a one-piece casting of a suitable superalloy, such as a nickel-, cobalt-, or iron-based superalloy, which has acceptable strength at the elevated temperatures of operation in a gas turbine engine. The plenum **214** can serve to eliminate material in non-essential areas of the airfoil **200**. This can result in reduction of the weight of the airfoil **200** which can have important

benefits, including reductions both in operating stresses and material costs. Additionally, the plenum 214 may create one or more desirable aerodynamic characteristics with respect to the shroud of the gas turbine engine, as described hereinafter.

FIG. 3 is a cross-sectional view of the airfoil 200 as seen along Line A-A in FIG. 2. As depicted in FIG. 3, the airfoil 200 can have a radial direction 216 which defines a center line of the body 202 as measured normal to the central hub at a location from which the airfoil 200 extends from. The radial direction 216 may be oriented generally perpendicular, i.e., normal, to an inner surface of the shroud of the gas turbine engine when the airfoil 200 is disposed therein. In the illustrated embodiment, the radial direction 216 intersects the plenum 214. The radial direction 216 is depicted as being normal to the outer edge 212 of the airfoil 200. In certain instances, the radial direction 216 may be defined as a line perpendicular relative to the outer edge 212 of the airfoil 200.

The plenum 214 can define a void disposed between a suction-side sidewall 218 and a pressure-side sidewall 220 of the body 202. The suction-side sidewall 218 can correspond with the side of the plenum 214 disposed nearest to the suction surface 204 while the pressure-side sidewall 220 can correspond with the side of the plenum 214 disposed nearest to the pressure surface 206. The suction-side sidewall 218 and pressure-side sidewall 220 can join together at opposite ends to form the laterally bounded plenum 214.

In the depicted embodiment, the suction-side sidewall 218 includes two segments—a first sidewall portion 222 and a second sidewall portion 224. The second sidewall portion 224 can be disposed adjacent to and radially outside of the first sidewall portion 222. In an embodiment, the second sidewall portion 224 can extend between the first sidewall portion 222 and the outer edge 212.

In an embodiment, the first sidewall portion 222 and second sidewall portion 224 can be immediately adjacent to one another and meet at a junction line extending into the page. In certain instances, the junction line can be spaced apart from the outer edge 212 of the airfoil 200 by a fixed distance, as measured along the length of the junction line. In other instances, the distance between the junction line and the outer edge 212 of the airfoil 200 can vary along the junction line. For example, the first sidewall portion 222 can have a first radial height, as measured parallel with the radial direction 216, at a first location of the plenum 214, and a second radial height, as measured parallel with the radial direction 216, at a second location of the plenum 214, wherein the first and second radial heights are different from one another. To create the variable height of the first sidewall portion 222, the height of the second sidewall portion 224 can inversely change, the depth of the plenum 214 can change, or both.

In an embodiment, the first and second sidewall portions 222 and 224 can be angularly offset from one another by an angle, β . That is, the first and second sidewall portions 222 and 224 can lie along lines, as viewed in cross section (e.g., as depicted in FIG. 3), that intersect one another at the junction line. By way of example, the first and second sidewall portions 222 and 224 can be angularly offset from one another by an angle, β , of at least 1° , such as at least 2° , such as at least 3° , such as at least 4° , such as at least 5° , such as at least 10° , such as at least 15° , such as by at least 20° . In an embodiment, the second sidewall portion 224 can be parallel, or substantially parallel, with the radial direction 216 of the airfoil 200 while the first sidewall portion 222 can be angularly offset from the radial direction 216 by the

aforementioned angular offset between the first and second sidewall portions 222 and 224. In an embodiment, the junction between the first and second sidewall portions 222 and 224 can occur at a sharp interface. In another embodiment, the junction between the first and second sidewall portions 222 and 224 can occur over a gradual transition, e.g., a rounded corner as viewed in cross section.

The pressure-side sidewall 220 is illustrated in FIG. 3 with a generally linear cross-sectional shape. The pressure-side sidewall 220 can be lie along a line parallel, or generally parallel, with the radial direction 216. Alternatively, the pressure-side sidewall can taper toward or away from the radial direction 216 at the outer edge 212. In another embodiment, the pressure-side sidewall 220 can have a non-linear cross-sectional shape, such as, for example, an arcuate cross-sectional shape, a segmented cross-sectional shape (e.g., similar to the suction-side sidewall 218), another non-linear cross-sectional shape, or any combination thereof. In the illustrated embodiment, a thickness of body 202, as measured between the pressure side 206 and the pressure-side sidewall 220, is shown as being generally constant. In other embodiments, the thickness of the body 202, as measured between the pressure side 206 of the airfoil 200 and the pressure-side sidewall 220 of the plenum 214 can vary as measured along the radial height of the body 202. In an embodiment, the pressure-side sidewall 220, or a portion thereof, can be parallel, or generally parallel, as viewed in cross section, with the second sidewall portion 224 of the suction-side sidewall 218.

The airfoil 200 can include a flared portion 226 extending from the suction side 204 of the airfoil 200. The flared portion 226 can extend from the body 202 of the airfoil in the axial direction (e.g., axial direction A as shown in FIG. 1). In an embodiment, the flared portion 226 can be integrally formed with the body 202 of the airfoil 200. That is, the body 202 of the airfoil 200 and flared portion 226 can be monolithically formed from a single piece. A dashed line 228 is shown in FIG. 3 to represent where traditional airfoils ends along the suction surface 204 in the axial direction. The flared portion 226 can introduce additional mass to the airfoil 200 along (i.e., adjacent to) the suction surface 204. In particular, the flared portion 226 can increase the mass of the airfoil 200 at the furthest radially outer portion of the body 202 (i.e., adjacent to the outer edge 212), thus having the greatest effect on the moment of inertia of the airfoil 200.

In an embodiment, the flared portion 226 can extend along less than 30% of a radial length of the airfoil 200, as measured between the outer edge 212 and the central hub of the airfoil 200, such as less than 25% of the radial length of the airfoil 200, such as less than 20% of the radial length of the airfoil 200, such as less than 19% of the radial length of the airfoil 200, such as less than 18% of the radial length of the airfoil 200, such as less than 17% of the radial length of the airfoil 200, such as less than 16% of the radial length of the airfoil 200, such as less than 15% of the radial length of the airfoil 200, such as less than 14% of the radial length of the airfoil 200, such as less than 13% of the radial length of the airfoil 200, such as less than 12% of the radial length of the airfoil 200, such as less than 11% of the radial length of the airfoil 200, such as less than 10% of the radial length of the airfoil 200. In a more particular embodiment, the flared portion 226 can extend along less than 8% of the radial length of the airfoil 200, such as along less than 6% of the radial length of the airfoil 200, such as along less than 4% of the radial length of the airfoil 200, such as along less than 2% of the radial length of the airfoil 200. As used herein, radial length is intended to refer to the length of the airfoil

200 in the radial direction as would be seen with the airfoil 200 operationally disposed within a gas turbine engine (e.g., the turbofan jet engine 10 depicted in FIG. 1). That is, reference to the radial direction is made with respect to an orientation of the airfoil 200 as part of a turbine or compressor within the gas turbine engine. In an embodiment, the flared portion 226 can extend from the outer edge 212 of the airfoil 200 toward the central hub. In a more particular embodiment, the flared portion 226 can be part of, i.e., define a portion of, the outer edge 212 of the airfoil 200.

In an embodiment, the flared portion 226 can extend along a distance less than the chord length, c , of the airfoil 200. That is, for example, referring again to FIG. 2, the length, L_{FP} , of the flared portion 226, as measured along the suction surface 204 can be less than the chord length, c , of the airfoil 200. By way of example, L_{FP} can be less than 0.99 c , such as less than 0.98 c , such as less than 0.97 c , such as less than 0.96 c , such as less than 0.95 c , such as less than 0.9 c , such as less than 0.85 c , such as less than 0.8 c , such as less than 0.75 c . In an embodiment, L_{FP} can be less than 0.7 c , such as less than 0.65 c , such as less than 0.6 c . In another embodiment, L_{FP} can be at least 0.1 c , such as at least 0.15 c , such as at least 0.2 c , such as at least 0.3 c , such as at least 0.4 c . In yet another embodiment, L_{FP} can be within a range of 0.1 c and 0.99 c , such as in a range of 0.25 c and 0.75 c . Flared portions 226 having lengths, L_{FP} , less than the chord length, c , can be referred to as mini flares. The flared portion 226 may be readily discernable on mini flares as the portion of the suction surface 204 disposed between the leading and trailing ends 208 and 210 and the mini flare will have a more traditional, i.e., non-flared, cross-sectional profile. In a particular instance, the flared portion 226 can be equally spaced apart from the leading and trailing ends 208 and 210 of the airfoil 200. In another instance, the flared portion 226 can be disposed closer to one of the leading and trailing ends 208 or 210. For example, the flared portion 226 can be skewed by up to 100% towards one of the leading and trailing ends 208 and 210.

In some embodiments, the flared portion 226 can define a linear cross-sectional surface profile, as seen for example in FIG. 3. That is, an exposed portion of the flared portion 226 can lie along a generally straight line as viewed in cross section. In other embodiments, the flared portion 226 can have an arcuate cross-sectional surface profile, such as a flared profile having an increasing cross-sectional surface profile angle, as measured, for example, with respect to the radial direction 216. In an embodiment, a tip 227 of the flared portion 226 may be sharp, e.g., an angled corner formed between the outer edge 212 of the airfoil 200 and the axial surface of the flared portion 226. In another embodiment, the tip 227 of the flared portion 226 can have a rounded or segmented cross-sectional profile.

In an embodiment, the flared portion 226 can elongate the outer edge 212 of the airfoil 200, as measured in the surface normal direction as compared to a traditional airfoil, by at least 0.1 mm, such as at least 0.5 mm, such as at least 1 mm, such as at least 2 mm, such as at least 5 mm. In another embodiment, the flared portion 226 can elongate the outer edge 212 of the airfoil 200, as measured in the axial direction as compared to a traditional airfoil, by at least 10 mm, such as at least 15 mm, such as at least 20 mm, such as at least 25 mm, such as at least 30 mm, such as at least 40 mm, such as at least 50 mm, such as at least 60 mm, such as at least 70 mm, such as at least 80 mm, such as at least 90 mm, such as at least 100 mm. In an embodiment, a thickness of body 202, T_{BS} , as measured between the suction surface 204 and the suction-side sidewall 218 at the outer edge 212 of the

airfoil 200, can be greater than the thickness of the body 202, T_{BP} , as measured between the pressure side 206 and the pressure-side sidewall 220 at the outer edge 212 of the airfoil 200. For example, T_{BS} can be at least 1.01 T_{BP} , such as at least 1.02 T_{BP} , such as at least 1.03 T_{BP} , such as at least 1.04 T_{BP} , such as at least 1.05 T_{BP} , such as at least 1.1 T_{BP} , such as at least 1.2 T_{BP} , such as at least 1.5 T_{BP} , such as at least 2 T_{BP} , such as at least 2.5 T_{BP} , such as at least 3 T_{BP} . In certain instances, T_{BS} may be no greater than 10 T_{BP} , such as no greater than 5 T_{BP} .

In an embodiment, the flared portion 226 can define a height, H_F , as measured in a direction perpendicular to the chord, that is greater than a largest axial dimension of the flared portion 226, A_F , as measured at the outer edge 212 of the airfoil 200. By way of example, H_F can be at least 1.01 A_F , such as at least 1.05 A_F , such as at least 1.1 A_F , such as at least 1.25 A_F , such as at least 1.5 A_F , such as at least 1.75 A_F , such as at least 2.0 A_F , such as at least 3.0 A_F , such as at least 4.0 A_F , such as at least 5.0 A_F , such as at least 10.0 A_F , such as at least 20.0 A_F .

The largest axial dimension of the flared portion 226, A_F , can be less than the thickness of the body 202, T_{BS} , as measured between the suction surface 204 and the suction-side sidewall 218. By way of example, A_F can be less than 0.9 T_{BS} , such as less than 0.85 T_{BS} , such as less than 0.8 T_{BS} , such as less than 0.75 T_{BS} , such as less than 0.7 T_{BS} , such as less than 0.65 T_{BS} , such as less than 0.6 T_{BS} , such as less than 0.55 T_{BS} , such as less than 0.5 T_{BS} , such as less than 0.45 T_{BS} , such as less than 0.4 T_{BS} , such as less than 0.35 T_{BS} , such as less than 0.3 T_{BS} , such as less than 0.25 T_{BS} , such as less than 0.2 T_{BS} .

In an embodiment, the suction surface 204 at the flared portion 226 can lie along a line angularly offset from the radial direction 216 of the airfoil 200 by an angle, α . The first sidewall portion 222 can be angularly offset from the radial direction 216 by the same, or substantially same, angle, α . The suction surface 204 at the flared portion 226 can be generally parallel with the first sidewall portion 222 of the suction-side sidewall 218, as measured at a same radial distance from the outer edge 212. That is, T_{BS} can be approximately equal at multiple, radially spaced apart planes intersecting the first sidewall portion 222 of the suction-side sidewall 218. This can occur where α is equal to β . Meanwhile, in accordance with an embodiment, T_{BS} can be different at multiple, radially spaced apart planes intersecting the second sidewall portion 224 of the suction-side sidewall 218. For example, T_{BS} can increase as the plane of measurement gets closer to the outer edge 212 of the airfoil 200. In certain instances, the rate of change of T_{BS} relative to the radial distance relative to the outer edge 212 can determine the relative amount of flaring occurring at the flared portion 226.

Still referring to FIG. 3, in certain instances, the flared portion 226 can be identified by a relative angular displacement between the suction surface 204 and the pressure surface 206, as measured at an approximately same location in the radial R direction (FIG. 1). The pressure surface 206 can be angularly offset from the radial direction 216 by an angle, γ , that is less than the angle α of the flared portion 226. For example, α can be at least 5 degrees less than γ , such as at least 10 degrees less than γ , such as at least 15 degrees less than γ , such as at least 20 degrees less than γ , such as at least 25 degrees less than γ , such as at least 30 degrees less than γ , such as at least 35 degrees less than γ , such as at least 40 degrees less than γ .

FIG. 4 illustrates a cross-sectional view of the airfoil 200 as seen in accordance with an embodiment. A shroud S of the

gas turbine engine is shown to depict a relative spacing between the outer edge **212** of the airfoil **200** and the shroud **S** when the airfoil **200** is installed in a gas turbine engine. In the illustrated embodiment, the outer edge **212** of the airfoil **200** is spaced apart from the shroud **S** by a clearance, **CLR**. In an embodiment, clearance, **CLR**, may be measured at operating temperatures and conditions, e.g., when the airfoil **200** is subjected to centripetal forces acting upon the rotating airfoil **200** which might cause the body **202** of the airfoil **200** to elongate in the radial direction. In an embodiment, the clearance, **CLR**, can be at least 0.01 mm, such as at least 0.05 mm, such as at least 0.1 mm, such as at least 0.5 mm, such as at least 1 mm, such as at least 1.5 mm, such as at least 2 mm, such as at least 3 mm, such as at least 4 mm, such as at least 5 mm. The height, **H**, of the plenum **214** is shown as measured from the outer edge **212** of the airfoil **200** to a radially inner surface of the plenum **214**. The height, **h**, of the second portion **224** is shown as measured from the outer edge **212**. The height of the first sidewall portion **222** may be equal to the height, **H**, of the plenum **214** minus the height, **h**, of the second portion **224**. In an embodiment, h/CLR is greater than 1.5, such as greater than 2, such as greater than 2.5, such as greater than 3, such as greater than 3.5, such as greater than 4, such as greater than 4.5, such as greater than 5. In this regard, the height of the second sidewall portion **224** can be greater than the clearance, **CLR**, between the outer edge **212** of the airfoil **200** and the shroud **S**. In certain instances, h/CLR can be impactful in affecting one or more aerodynamic characteristics of the airfoil **200**, as described in greater detail hereinafter. While H/CLR may be impactful in affecting the aerodynamic characteristics of the airfoil **200**, h/CLR being greater than 1.5 may improve the one or more aerodynamic characteristics while inclusion of the first sidewall portion **222** can minimize the resulting weight of the airfoil **200**.

In an embodiment, the clearance, **CLR**, between the outer edge **212** of the airfoil **200** and the shroud **S** can be approximately uniform at all locations along the outer edge **212** of the airfoil **200**. In another embodiment, the clearance, **CLR**, can vary along the outer edge **212**. For instance, the clearance of the outer edge **212** as measured at the pressure surface **206** can be different from the clearance of the outer edge **212** as measured at the suction surface **204** or another location therebetween.

FIG. 7 illustrates an enlarged view of an interface formed between the outer edge **212** of the airfoil **200** and an inner surface of the shroud **S** as seen in circle B in FIG. 4. Lines $A_1, A_2, A_3, A_4, A_5,$ and A_6 illustrate exemplary flow paths of air from the plenum **214** as the air paths pass through the clearance, **CLR**, between the airfoil **200** and shroud **S**. The sharp edge **700** formed between the second sidewall portion **224** of the suction-side surface **218** of the plenum **214** and the outer edge **212** of the airfoil **200** can cause air passing between the airfoil **200** and shroud **S** to compress in the radial direction, generating the formation of an air gap **G** and a vena contracta effect where the air stream cross-sectional area is the smallest and the air velocity is the largest. Generation of the air gap **G** at the sharp edge **700**, thereby creating the vena contracta effect, can enhance the aerodynamic characteristics of the airfoil **200**, improving performance and aerodynamic efficiencies of the gas turbine engine. In this regard, having the second sidewall portion **224** generally normal with the shroud **S** and/or radial direction **216** can be beneficial for engine performance.

In contrast, FIG. 5 illustrates an airfoil **500** without a plenum sidewall having an angle normal to the shroud **S**, as seen adjacent to the outer edge **212** of the airfoil **500**.

Instead, the plenum sidewall illustrated in FIG. 5 is generally linear and angularly offset from the radial direction **216** as measured at the outer edge **212**. FIG. 6 illustrates an enlarged view of the interface formed between the airfoil **500** and shroud **S** as seen in Circle C in FIG. 5. As illustrated, the vena contracta effect of the airfoil **500** is diminished as compared to that exhibited by the airfoil **200** depicted in FIG. 7 as a result of the angularly offset plenum sidewall. Notably, the air gap **G** is reduced in size, resulting in a larger cross-sectional area for air to pass through the clearance between the outer edge **212** of the airfoil **500** and the shroud **S**. In turn, engine performance is reduced as the airfoil **500** is less aerodynamically efficient.

Accordingly, use of a sharp edge **700** (FIG. 7) is advantageous in creating a desirable aerodynamic characteristic. Referring again to FIG. 4, dashed line X depicts an exemplary view of the suction-side surface **218** with the entire surface oriented parallel with the radial direction **216**. That is, unlike the suction-side surface **218** previously described including the first sidewall portion **222** and second sidewall portion **224**, the dashed line X represents an example of the suction-side surface **218** if the entire radial height **H** of the suction-side surface **218** of the plenum **214** were oriented parallel with the radial direction **216** while affording sufficient strength to the flared portion **226**. When using flared portions **226**, the inclusion of such a linear side surface **218** adds unnecessary weight to the airfoil **200** at the radially outermost portion there along, most affecting the centripetal forces acting on the airfoil **200**. Specifically, the wall thickness between the suction surface **204** and the side surface **218** of the plenum **214** becomes unnecessarily large as a result of including the flared portion **226**.

Accordingly, use of a dual-angled suction-side surface **218**, as depicted in FIG. 4 and as previously described, including first and second sidewall portions **222** and **224** can enhance aerodynamic performance while reducing unnecessary weight associated with an entirely linear suction-side surface **218** oriented parallel with the radial direction **216**.

FIG. 8 illustrates a view of an airfoil **800** in accordance with an embodiment herein as seen along the radial direction of the airfoil **800** looking perpendicular to the outer edge **812** thereof. The airfoil **800** can have any one or more features similar to the airfoil **200** previously described. The plenum **814**, for example, is depicted extending between the leading and trailing ends **808** and **810**. Located adjacent to the plenum **814** is a recess **830** which extends from the outer edge **812** into the airfoil **800**. The recess **830** is shown disposed between the plenum **814** and the flared portion **826**. In an embodiment, the recess **830** extends a distance along the airfoil **200** less than a distance of the plenum **814**. In another embodiment, the recess **830** and plenum **814** can have the same lengths, as measured between the leading and trailing ends **808** and **810**. In yet another embodiment, the recess **830** can have a length greater than the length of the plenum **814**.

FIG. 9 illustrates a cross-sectional view of the airfoil **800** shown in FIG. 8 as seen along Line B-B. The plenum **814** defines a depth D_P , as measured from the outer edge **812**, greater than a depth, D_R , of the recess **830**, as measured from the outer edge **812**. In an embodiment, D_P can be at least $1.01 D_R$, such as at least $1.05 D_R$, such as at least $1.1 D_R$, such as at least $1.25 D_R$, such as at least $1.5 D_R$, such as at least $1.75 D_R$, such as at least $2.0 D_R$. In another embodiment, D_P can be no greater than $200 D_R$, such as no greater than $100 D_R$, such as no greater than $25 D_R$, such as no greater than $10 D_R$. In some instances, the depth, D_R , of the recess **830** can be uniform, or generally uniform, along the

entire recess **830**. In other instances, the depth, D_R , of the recess **830** can vary along the recess **830**. For example, the recess **830** can have a first depth, D_{R1} , at a first location, and a second depth, D_{R2} , at a second location different from the first location.

The recess **830** includes first and second sidewalls **832** and **834**. The first sidewall **832** is shown with an angularly offset surface as compared to the radial direction of the airfoil **800** while the second sidewall **834** is shown with a surface generally parallel with the radial direction of the airfoil **800**. In another embodiment, the first and second sidewalls **832** and **834** of the recess **830** can be parallel, or approximately parallel, with one another. In another embodiment, the second sidewall **834** (closer to the plenum **814**) can be angularly offset from the radial direction of the airfoil **800** and the first sidewall **832** (closer to the flared portion **826**) can be parallel with the radial direction of the airfoil **800**.

In the illustrated embodiment, the first and second sidewalls **832** and **834** lie along generally straight lines, as seen in cross section. In another embodiment, at least one of the first and second sidewalls **832** and **834** can have an arcuate and/or multi-segmented sidewall contour. In an embodiment, an angle formed between the first and second sidewalls **832** and **834** can be at least 1° , such as at least 5° , such as at least 10° , such as at least 15° . In another embodiment, the angle between the first and second sidewalls **832** and **834** can be no greater than 89° , such as no greater than 60° , such as no greater than 45° .

The recess **830** can define an aspect ratio $[L_R:W_R]$ as measured by a relative length, L_R , of the recess **830** as compared to a relative width, W_R , thereof. In an embodiment, the aspect ratio can be between approximately 500:1 and 2:1, such as between 100:1 and 2.5:1, such as between 50:1 and 3:1. The recess **830** can further define another aspect ratio $[L_R:D_R]$ as measured by the relative length, L_R , of the recess **830** as compared to a relative depth, D_R , thereof. In an embodiment, the aspect ratio can be between approximately 100:1 and 5:1, such as between 750:1 and 10:1, such as between 500:1 and 20:1. In certain instances, the recess **830** can enhance performance of the airfoil **800**, such as improve aerodynamic performance, along the outer edge **812**.

FIGS. **10** and **11** illustrate an airfoil **1000** having any one or more similar characteristics as described with respect to the airfoils **200** and **800** previously described herein. For example, the airfoil **1000** can include a plenum **1014** extending from an outer edge **1012** of the airfoil **1000** and a flared portion **1026** at the suction surface **1004**. FIG. **10** is an axial view of the airfoil **1000** as seen along the radial direction. FIG. **11** is a cross-sectional view of the airfoil **1000** as seen along Line C-C in FIG. **10**.

In certain embodiments, the airfoil **1000** can include a cooling cavity **1036** disposed within the airfoil **1000**. Use of a cooling cavity **1036** may be particularly useful for stage one turbine blades which operate within areas of the gas turbine engine having very high temperatures, e.g., areas of the gas turbine engine located adjacent to the combustion area. In an embodiment, the cooling cavity **1036** can include a single volumetric cavity. In another embodiment, the cooling cavity **1036** can include a plurality of cooling cavities, such as a plurality of interconnected cooling cavities. The cooling cavity **1036** can be in fluid communication with the outer edge **1012** of the airfoil **1000** through one or more cooling holes **1038**. The one or more cooling holes **1038** can extend, for example, from the cooling cavity **1036** to the outer edge **1012** and pass between the plenum **1014**

and flared portion **1026**. The one or more cooling holes **1036** can define a length, L_L , as measured between the cooling cavity **1036** and the outer edge **1012**. In an embodiment, all of the one or more cooling holes **1036** can have the same lengths, L_L , as compared to one another. In another embodiment, at least two of the one or more cooling holes **1036** can have different lengths, L_L , as compared to one another. The one or more cooling holes **1036** can define cross-sectional sizes, e.g., diameters, and/or shapes as measured normal to the length, L_L . In an embodiment, the one or more cooling holes **1036** can all have the same cross-sectional sizes and/or shapes as compared to one another. In another embodiment, at least two of the one or more cooling holes **1036** can have different cross-sectional sizes and/or shapes as compared to one another.

In an embodiment, the one or more cooling holes **1038** can include a single cooling hole **1036**. In another embodiment, the one or more cooling holes **1038** can include at least two cooling holes, such as at least three cooling holes, such as at least four cooling holes, such as at least five cooling holes, such as at least six cooling holes, such as at least seven cooling holes, such as at least eight cooling holes, such as at least nine cooling holes, such as at least ten cooling holes, such as at least twenty cooling holes, such as at least fifty cooling holes. In an exemplary embodiment with a plurality of cooling holes **1038**, at least three of the cooling holes **1038**, such as all of the cooling holes **1038**, can be equidistantly spaced apart from one another. In another exemplary embodiment with a plurality of cooling holes **1038**, at least three of the cooling holes **1038**, such as all of the cooling holes **1038** can be spaced apart from one another by different distances. For example, a first adjacent pair of cooling holes **1038** can be spaced apart by a first distance different than a distance between a second adjacent pair of cooling holes **1038**.

As depicted in FIG. **11**, in accordance with one or more embodiments, at least one of the one or more cooling holes **1038** can lie along lines that are angularly offset from the radial direction of the airfoil **1000**. In other embodiments, at least one of the one or more cooling holes **1038** can be parallel, or substantially parallel, with the radial direction of the airfoil **1000**. In another embodiment, at least one of the one or more cooling holes **1038** can include a plurality of segmented portions, i.e., a plurality of linear or arcuate sections joined together.

The one or more cooling holes **1038** can be in fluid communication with the cooling cavity **1036** and provide cooled fluid, e.g., cooled air, from the cooling cavity **1036** to the outer edge **1012** of the airfoil **1000**.

FIGS. **12** and **13** illustrate another embodiment of the airfoil **1000**. Similar to the embodiment illustrated in FIGS. **10** and **11**, the airfoil **1000** of FIGS. **12** and **13** include one or more cooling holes **1038**. However, unlike the embodiment illustrated in FIGS. **10** and **11**, the cooling holes **1038** terminate at the outer edge **1012** at an enlarged area **1040**. In an embodiment, the enlarged area **1040** can include a cooling hole extension substantially similar to the cooling hole **1038** but having a larger size and/or shape as compared to the underlying cooling hole **1038**. By way of example, at least one of the one or more cooling holes **1038** can define a first dimension, e.g., a first diameter, as measured at a first location along the length, L_L , of the cooling hole **1038**, and a second dimension, e.g., a second diameter, as measured at a second location along the length, L_L , of the cooling hole **1038** adjacent to the outer edge **1012**, where the second size is greater than the first size. For instance, the second size can be at least 101% the first size, such as at least 105% the first

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size, such as at least 110% the first size, such as at least 125% the first size. In another embodiment, the second size is no greater than 1000% the first size.

In the depicted embodiment, the enlarged area **1040** comprises a channel extending between the one or more cooling holes **1038**. That is, the enlarged area **1040** extends continuously between adjacent cooling holes **1038**. In such a manner, the cooling holes **1038** can be in fluid communication with one another through the channel adjacent to the outer edge **1012** of the airfoil **1000**. This can result in increased cooling and circulation along the outer edge **1012** of the airfoil **1000**. In an embodiment, the channel connecting the cooling holes **1038** can have a consistent shape and/or size as measured along the channel. In another embodiment, at least one of the shape and size of the channel can fluctuate or vary at different locations along the channel. For example, the channel may have a minimum depth, as measured from the outer edge **1012**, at a midpoint between adjacent cooling holes **1038**.

Airfoils are generally permitted to deform by a prescribed tolerance during use. Such deformation can be created by materials operating at high velocities, under high loads, at high temperatures. It is not uncommon for the outer edges of airfoils to occasionally come into contact with the shroud. When such contact occurs, the use of cooling holes **1038** may be mitigated by scraped material from the outer edge of the airfoil closing the entrance to the cooling hole **1038**. Use of an enlarged area **1040** at the outer edge **1012** of the cooling hole **1038** can prevent the cooling hole **1038** from closing shut if the airfoil **1000** radially expands during operation and contacts the shroud S. That is, the enlarged area **1040** of the cooling hole **1038** at the outer edge **1012** can allow for some degree of contact between the airfoil **1000** and shroud S without substantially, or entirely, closing the cooling hole **1038**.

FIGS. **14** and **15** depict another embodiment of the airfoil **1000** similar to those depicted in FIGS. **10** to **13**. The enlarged area **1040** is depicted with a tapered profile, e.g., tapering from a size of the cooling hole **1038** to an enlarged size, as measured at the outer edge **1012**. The tapered profile is shown having a curved taper. FIGS. **16** and **17** illustrate an embodiment of the airfoil **1000** where the enlarged area **1040** has a linear taper, as measured from the cooling hole **1038** to the outer edge **1012** of the airfoil **1000**. Moreover, the embodiment illustrated in FIGS. **16** and **17** does not interconnect the enlarged area **1040** of adjacent cooling holes **1038**. Instead, each enlarged area **1040** depicted in FIGS. **16** and **17** is part of a discrete cooling hole **1038**. It should be understood that aspects of the exemplary embodiments illustrated in FIGS. **10** to **17** can be combined in any number of combinations and are not limited to those combinations as explicitly illustrated in the Figures.

In general, airfoils described herein can exhibit increased aerodynamic performance without adding unnecessary weight to the outer edge thereof. In such a manner, the airfoil described herein can generate increased performance without decreasing engine efficiency or durability.

This written description uses examples to disclose the invention, including the best mode, and also to enable any person skilled in the art to practice the invention, including making and using any devices or systems and performing any incorporated methods. The patentable scope of the invention is defined by the claims, and may include other examples that occur to those skilled in the art. Such other examples are intended to be within the scope of the claims if they include structural elements that do not differ from the literal language of the claims, or if they include equivalent

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structural elements with insubstantial differences from the literal languages of the claims.

Further aspects of the invention are provided by the subject matter of the following clauses:

Embodiment 1. An airfoil for a gas turbine engine defining a radial direction and an axial direction, the airfoil comprising: a flared portion extending from a suction surface of the airfoil at an outer edge of the airfoil along the radial direction; and a plenum disposed at the outer edge of the airfoil, the plenum having a suction-side sidewall and a pressure-side sidewall, wherein the suction-side sidewall has a first sidewall portion adjacent to a second sidewall portion disposed outside of the first sidewall portion along the radial direction, wherein the first sidewall portion defines a first angle with a radial direction of the airfoil as measured by an average angular offset between the radial direction and the first sidewall portion, wherein the second sidewall portion defines a second angle with the radial direction of the airfoil as measured by an average angular offset between the radial direction and the second sidewall portion, and wherein the first angle is greater than the second angle.

Embodiment 2. The airfoil of any one of the embodiments, wherein the outer edge of the airfoil is configured to be spaced apart from a shroud of the gas turbine engine by a clearance distance, CLR, wherein the second sidewall portion has a radial height, h, and wherein h/CLR is greater than 2.

Embodiment 3. The airfoil of any one of the embodiments, wherein a suction surface of the flared portion is angularly offset from the radial direction of the airfoil by a third angle as measured by an average angular offset between the radial direction and the surface of the flared portion, and wherein the third angle is approximately equal to the first angle.

Embodiment 4. The airfoil of any one of the embodiments, wherein the airfoil further comprises a cooling cavity disposed within a body of the airfoil, and wherein the cooling cavity is in fluid communication with the outer edge of the airfoil through one or more cooling holes extending between the cooling cavity and the outer edge of the airfoil.

Embodiment 5. The airfoil of any one of the embodiments, wherein at least one of the one or more cooling holes comprises a first size, as measured at a first radial location along the one or more cooling holes, and a second size, as measured at a second radial location along the one or more cooling holes, the second radial location being radially outside the first radial location, and wherein the second size is greater than the first size.

Embodiment 6. The airfoil of any one of the embodiments, wherein the second radial location corresponds with the outer edge of the airfoil.

Embodiment 7. The airfoil of any one of the embodiments, wherein the flared portion extends less than 80% of a chord length, c, of the airfoil, as measured at the outer edge of the airfoil.

Embodiment 8. The airfoil of any one of the embodiments, wherein the flared portion is spaced apart from a trailing edge of the airfoil and a leading edge of the airfoil.

Embodiment 9. The airfoil of any one of the embodiments, wherein the flared portion has a tapered profile.

Embodiment 10. The airfoil of any one of the embodiments, wherein the outer edge of the airfoil defines a recess disposed between and spaced apart from the plenum and a suction surface of the flared portion, as measured at the outer edge of the airfoil.

Embodiment 11. A gas turbine engine defining a radial direction, the gas turbine engine comprising: a shroud; and

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a turbine positioned at least partially inward of the shroud along the radial direction, the turbine having a plurality of turbine rotor blades, wherein at least one of the plurality of turbine rotor blades comprises: a flared portion extending from a suction surface of the airfoil at an outer edge of the airfoil; and a plenum disposed at the outer edge of the airfoil, the plenum having a suction-side sidewall and a pressure-side sidewall, wherein the suction-side sidewall has a first sidewall portion adjacent to a second sidewall portion disposed radially outside of the first sidewall portion, wherein the second sidewall portion is approximately normal relative to an inner surface of the shroud, and wherein the first sidewall portion is angularly offset from the second sidewall portion.

Embodiment 12. The gas turbine engine of any one of the embodiments, wherein the at least one of the plurality of turbine rotor blades comprises all of the plurality of turbine rotor blades.

Embodiment 13. The gas turbine engine of any one of the embodiments, wherein the outer edge of the airfoil is spaced apart from the shroud by a clearance distance, CLR, wherein the second sidewall portion has a radial height, h, and wherein h/CLR is greater than 2.

Embodiment 14. The gas turbine engine of any one of the embodiments, wherein the first sidewall portion and second sidewall portion lie along best fit lines that intersect at a junction having a junction angle, β , of at least 5° .

Embodiment 15. The gas turbine engine of any one of the embodiments, wherein the flared portion extends no greater than 80% of a chord length of the airfoil, as measured at the outer edge of the airfoil, and wherein the flared portion is spaced apart from a trailing edge of the airfoil and a leading edge of the airfoil.

Embodiment 16. The gas turbine engine of any one of the embodiments, wherein the airfoil further comprises a cooling cavity disposed within a body of the airfoil, and wherein the cooling cavity is in fluid communication with the outer edge of the airfoil through one or more cooling holes extending between the cooling cavity and the outer edge of the airfoil.

Embodiment 17. An airfoil for a gas turbine engine defining a radial direction and an axial direction, the airfoil comprising: a flared portion extending from a suction surface of the airfoil along less than 20% of a radial length of the airfoil, as measured from an outer edge of the airfoil along the radial direction, wherein the flared portion extends less than 80% of a chord length, c, of the airfoil, as measured at the outer edge of the airfoil.

Embodiment 18. The airfoil of any one of the embodiments, wherein the airfoil further comprises: a body having a plenum disposed at the outer edge, the plenum having a suction-side sidewall and a pressure-side sidewall, wherein the suction-side sidewall has a first sidewall portion adjacent to a second sidewall portion disposed radially outside of the first sidewall portion, wherein the second sidewall portion is approximately parallel with a radial direction of the airfoil, and wherein the first sidewall portion is angularly offset from the radial direction of the airfoil.

Embodiment 19. The airfoil of any one of the embodiments, wherein a suction surface of the airfoil is angularly offset from the radial direction of the airfoil by an angle, a, as measured by an average angular offset between the radial direction and the suction surface of the airfoil, and wherein the first sidewall portion is angularly offset by an angle of approximately α , as measured by an average angular offset between the radial direction and the first sidewall portion.

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Embodiment 20. The airfoil of any one of the embodiments, wherein a surface of the flared portion is disposed at an angle, α , as measured relative to the radial direction, wherein a pressure surface of the airfoil is disposed at an angle, γ , as measured relative to the radial direction at an approximately same relative height in the radial direction as α , and wherein γ is less than α .

What is claimed is:

1. An airfoil for a gas turbine engine defining a radial direction, the airfoil comprising:

a flared portion extending from a suction surface of the airfoil at an outer edge of the airfoil along the radial direction, the flared portion spaced apart from a trailing edge of the airfoil and a leading edge of the airfoil; and a plenum disposed at an outer edge of the airfoil, the plenum having a suction-side sidewall and a pressure-side sidewall;

wherein the suction-side sidewall has a first sidewall portion adjacent to a second sidewall portion disposed radially outside of the first sidewall portion;

wherein the first sidewall portion defines a first angle with the radial direction as measured by an average angular offset between the radial direction and the first sidewall portion; and

wherein the second sidewall portion defines a second angle with the radial direction, less than the first angle, as measured by an average angular offset between the radial direction and the second sidewall portion.

2. The airfoil of claim 1, wherein the outer edge of the airfoil is configured to be spaced apart from a shroud of the gas turbine engine by a clearance distance, CLR, wherein the second sidewall portion has a radial height, h, and wherein h/CLR is greater than 2.

3. The airfoil of claim 1, wherein a suction surface of the flared portion is angularly offset from the radial direction of the airfoil by a third angle as measured by an average angular offset between the radial direction and the suction surface of the flared portion, and wherein the third angle is approximately equal to the first angle.

4. The airfoil of claim 1, wherein the airfoil further comprises a cooling cavity disposed within a body of the airfoil, and wherein the cooling cavity is in fluid communication with the outer edge of the airfoil through one or more cooling holes extending between the cooling cavity and the outer edge of the airfoil.

5. The airfoil of claim 4, wherein at least one of the one or more cooling holes comprises a first size, as measured at a first radial location along the one or more cooling holes, and a second size, as measured at a second radial location along the one or more cooling holes, the second radial location being radially outside the first radial location, and wherein the second size is greater than the first size.

6. The airfoil of claim 5, wherein the second radial location corresponds with the outer edge of the airfoil.

7. The airfoil of claim 1, wherein the flared portion extends less than 80% of a chord length, c, of the airfoil, as measured at the outer edge of the airfoil.

8. The airfoil of claim 1, wherein the flared portion has a tapered profile.

9. The airfoil of claim 1, wherein the outer edge of the airfoil defines a recess disposed between and spaced apart from the plenum and a suction surface of the flared portion, as measured at the outer edge of the airfoil.

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10. A gas turbine engine defining a radial direction, the gas turbine engine comprising:
 a shroud; and
 a turbine positioned at least partially inward of the shroud along the radial direction, the turbine having a plurality of airfoils, with at least one airfoil in the plurality of airfoils comprising:
 a flared portion extending from a suction surface of the airfoil at an outer edge of the airfoil; and
 a plenum disposed at the outer edge of the airfoil, the plenum having a suction-side sidewall and a pressure-side sidewall;
 wherein the flared portion extends no greater than 80% of a chord length of the airfoil, as measured at an outer edge of the airfoil, and is spaced apart from a trailing edge and a leading edge of the airfoil;
 wherein the suction-side sidewall has a first sidewall portion adjacent to a second sidewall portion disposed radially outside of the first sidewall portion;
 wherein the second sidewall portion is approximately normal to an inner surface of the shroud; and
 wherein the first sidewall portion is angularly offset from the second sidewall portion.

11. The gas turbine engine of claim 10, wherein the outer edge of the at least one airfoil is spaced apart from the shroud by a clearance distance, CLR, wherein the second sidewall portion has a radial height, h, and wherein h/CLR is greater than 2.

12. The gas turbine engine of claim 10, wherein the first sidewall portion and the second sidewall portion lie along best fit lines that intersect at a junction having a junction angle, β , of at least 5° .

13. The gas turbine engine of claim 10, wherein the at least one airfoil further comprises a cooling cavity disposed within a body of the at least one airfoil, and wherein the cooling cavity is in fluid communication with the outer edge of the at least one airfoil through one or more cooling holes extending between the cooling cavity and the outer edge of the at least one airfoil.

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14. The gas turbine engine of claim 10, wherein each airfoil in the plurality of airfoils comprises the flared portion and the plenum.

15. An airfoil for a gas turbine engine defining a radial direction, the airfoil comprising:

a body having an outer edge and a plenum disposed at the outer edge, the plenum having a suction-side sidewall and a pressure-side sidewall; and

a flared portion extending radially from a suction surface of the airfoil along less than 20% of a radial length of the airfoil, as measured from an outer edge of the airfoil, and also extending less than 80% of a chord length of the airfoil, as measured at the outer edge of the airfoil;

wherein the suction-side sidewall has a first sidewall portion adjacent to a second sidewall portion disposed radially outside of the first sidewall portion;

wherein the second sidewall portion is approximately parallel with the radial direction; and

wherein the first sidewall portion is angularly offset from the radial direction.

16. The airfoil of claim 15, wherein a suction surface of the airfoil is angularly offset from the radial direction of the airfoil by an angle, α , as measured by an average angular offset between the radial direction and the suction surface of the airfoil, and wherein the first sidewall portion is angularly offset by an angle of approximately α , as measured by an average angular offset between the radial direction and the first sidewall portion.

17. The airfoil of claim 15, wherein a surface of the flared portion is disposed at an angle, a , as measured relative to the radial direction, wherein a pressure surface of the airfoil is disposed at an angle, γ , as measured relative to the radial direction at an approximately same relative height in the radial direction as α , and wherein γ is less than α .

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